

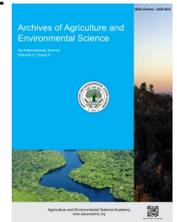


e-ISSN: 2456-6632

This content is available online at AESA

Archives of Agriculture and Environmental Science

Journal homepage: journals.aesacademy.org/index.php/aaes



REVIEW ARTICLE



Fusarium wilt of banana (Tropical Race 4) in Nepal: Distribution, epidemiology, and integrated management strategies

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ARTICLE HISTORY

Received: 08 September 2025

Revised received: 13 November 2025

Accepted: 23 November 2025

Keywords

Biological control

Biosecurity

Diagnostics

Epidemiology

Integrated disease management

ABSTRACT

Banana (*Musa* spp.) is a key smallholder crop in Nepal, ranking third in production ($\approx 282,000$ t yr^{-1}) and fifth in area ($\approx 19,000$ ha), yet it faces a growing threat from Fusarium wilt (Panama disease) caused by *Fusarium oxysporum* f. sp. *cubense* Tropical Race 4 (TR4). Unlike earlier epidemics that devastated 'Gros Michel' (Race 1), TR4 infects Cavendish and many cooking cultivars, persists in soil for over 30 years, and spreads through contaminated planting material, soil, water, and tools. This review aims to synthesize global and regional evidence on TR4's etiology, history, distribution, symptoms, and epidemiology, and to evaluate management options relevant to Nepal's smallholder systems following the country's first detections in 2023 (e.g., Kailali, Tikapur). Information was compiled systematically from peer-reviewed literature (Elsevier, Springer, Wiley), institutional reports (FAO, IPPC, NPPO), and verified bulletins (2000–2024). The synthesis indicates that curative control is unreliable, whereas integrated exclusion and containment strategies—certified disease-free planting material, field sanitation, and movement restrictions—can reduce disease incidence by 60–80%. Biological control, nutrient management, and tolerant cultivars show potential as supportive, not substitutive, measures. Therefore, establishing national diagnostic and surveillance capacity, strengthening on-farm biosecurity and clean-seed systems, and aligning regional quarantine and seed-certification policies should be needed on urgent priorities in Nepal. This study provides the first comprehensive synthesis of TR4's threat to Nepal, offering an evidence-based roadmap for safeguarding banana livelihoods and sustaining the national value chain.

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Citation of this article: Pantha, A., Poudel, P., Khanal, S., Karki, S., & Dhakal, N. (2025). Fusarium wilt of banana (Tropical Race 4) in Nepal: Distribution, epidemiology, and integrated management strategies. *Archives of Agriculture and Environmental Science*, 10(4), 692-701, <https://dx.doi.org/10.26832/24566632.2025.1004019>

INTRODUCTION

Bananas (*Musa paradisiaca*; family Musaceae) are a cornerstone fruit crop of tropical and subtropical food systems, cultivated on more than 8.8 million hectares and consumed as a staple by hundreds of millions (Maseko *et al.*, 2024). Domestication in Southeast Asia involved both species and underwent intra- and inter-specific hybridization between the two wild diploids *Musa acuminata* (AA) and *M. balbisiana* (BB), which contributed the A and B genomes to a broad array of cultivated cytotypes—diploids,

triploids, and tetraploids—resulting in nearly 1,000 banana cultivars worldwide (Heslop-Harrison & Schwarzacher, 2007). By production volume and trade value, banana is among the world's top ten staple foods (FAO, 2017), underpinning rural livelihoods and export earnings in major producer countries such as India, China, Ecuador, the Philippines, and Indonesia. The global banana industry has been projected to grow at roughly 4.5% between 2022 and 2027 (FAO/PPC, 2022). In Nepal, banana ranks fifth by cultivated area and third by output, underscoring its importance to farm income, employment, and nutrition (FDD, 2017).

This trajectory is increasingly threatened by *Fusarium* wilt of banana (Panama disease), caused by the soil-borne fungus *Fusarium oxysporum* f. sp. *cubense* (Foc). Among its recognized physiological races, Tropical Race 4 (TR4) has emerged as the most virulent and globally devastating, owing to its ability to infect a wide range of *Musa* cultivars, persist in soil for decades, and resist chemical eradication. The first confirmed detection of Foc TR4 in Nepal in 2023 (Pant et al., 2023) represents a major phytosanitary emergency for the national banana industry. Nepal's banana sector is dominated by smallholders who often rely on informal, unregulated planting material networks, with limited nursery hygiene and field sanitation. These systemic vulnerabilities make Nepal's production landscape highly conducive to TR4 establishment and spread, especially across interconnected districts through contaminated tools, irrigation water, and soil movement (FAO TR4 Global Network, 2025). While global reviews summarize TR4 biology and management, practical, context-specific guidance for Nepal remains fragmented. Smallholder-dominated production, informal movement of planting material, and variable nursery/field hygiene create conditions under which standard recommendations (e.g., strict biosecurity, certified planting material, water and soil sanitation) can be difficult to implement consistently. Evidence on diagnostics suitable for low-resource laboratories, farm-gate containment after first detection (isolation, roguing, sanitation, fallow, replant choices), varietal options relevant to Nepal, and workable surveillance and certification policies is dispersed across technical reports and case studies. This implementation gap results in inconsistent extension messages and uncertainty for growers and regulators about feasible near-term actions.

Despite the pathogen's global significance, there is a striking lack of peer-reviewed research and synthesized guidance specifically addressing TR4 under Nepal's production conditions. While international reviews (Ploetz, 2015; Dita et al., 2018; Kema et al., 2021) have examined TR4 biology, epidemiology, and management, practical insights for low-resource, smallholder-based systems like Nepal's remain scattered across technical reports and case studies. No comprehensive review has yet consolidated evidence on Nepal's 2023 outbreak, the associated management gaps, or policy-level response needs. This review therefore provides the first systematic synthesis of global and national evidence contextualized to Nepal's emerging TR4 scenario. The significance of this work lies in translating international knowledge into actionable recommendations for Nepal's context—particularly on diagnostics, surveillance, seed-system reform, and farm-level biosecurity practices that are feasible within smallholder constraints. Addressing these aspects is critical to mitigate yield loss, protect farmer livelihoods, and prevent cross-border dissemination. This study also identifies priority areas for national research—such as resistant variety testing, diagnostic standardization, and integrated disease management (IDM) frameworks—to guide policy and extension in the coming years. Against this backdrop, a consolidated, context-specific synthesis is warranted. This review appraises current knowledge on Foc TR4 with four objectives:

(i) to situate Nepal's emergence of TR4 within the global distribution and impact of *Fusarium* wilt; (ii) to summarize host range, symptomatology, and diagnostics relevant to rapid recognition; (iii) to synthesize epidemiology and spread mechanisms that shape outbreak dynamics; and (iv) to evaluate management and control options, emphasizing feasible components of integrated disease management (IDM) for Nepal's production systems while drawing on international experience. By integrating dispersed global and national evidence, this review aims to fill a critical knowledge gap and serve as a scientific and operational reference for research, surveillance, and extension agencies responding to the recent TR4 outbreak in Nepal.

METHODOLOGY

This review adopted a systematic approach to collect, evaluate, and synthesize secondary information on *Fusarium oxysporum* f. sp. *cubense* Tropical Race 4 (TR4) and its recent emergence in Nepal. All data were obtained from peer-reviewed journals, institutional reports, and credible digital repositories to ensure scientific reliability. A structured search was conducted across major databases—Google Scholar, Scopus, Web of Science, PubMed, and AGRIS—and specialized platforms such as the FAO TR4 Global Network, CABI Compendium, and ProMusa (CABI, 2021). The search was focused on literature from 2000 to September 2025 to capture modern developments, but seminal historical works were also included for context. Government sources including the Nepal Agricultural Research Council (NARC), MoALD (2022), Food and Agriculture Organization of the United Nations (FAO), International Plant Protection Convention (IPPC), and Biosecurity Queensland were also consulted. Recent outbreak details were cross-verified using recognized Nepali news portals (ShareSansar, 2023).

Search terms combined controlled and free keywords such as “*Fusarium* wilt,” “Panama disease,” “Tropical Race 4,” “banana TR4 Nepal,” “biosecurity,” and “integrated disease management,” using Boolean operators (AND/OR) for refinement. Inclusion criteria emphasized studies on TR4 etiology, epidemiology, diagnostics, and management; exclusion criteria eliminated unrelated or non-verifiable materials. Approximately 120 relevant publications were screened and synthesized thematically across etiology, distribution, symptomatology, and management frameworks. Priority was given to studies from FAO (2019), Dita et al. (2018), and Pant et al. (2023), along with recent government and extension documents. This methodological design ensures transparency and replicability by integrating scientific and applied perspectives to generate an evidence-based synthesis of TR4's epidemiology, management strategies, and policy implications tailored to Nepal's smallholder-dominated banana sector.

ETIOLOGY

Fusarium oxysporum f. sp. *Cubense* (Foc) is an asexual (mitosporic) ascomycete fungus and the causal agent of Panama wilt (Panama disease) in banana (Ploetz, 2006; Snyder & Hansen,

Table 1. Differential pathogenicity of Foc (R1–R4).

Race	Primary susceptible groups/cultivars	Reference
R1	Gros Michel (AAA); Manzano/Apple/Latundan (Silk, AAB)	Ploetz (2006)
R2	Cooking bananas of the Bluggoe subgroup (ABB)	Ploetz (2006)
R3	Affects <i>Heliconia</i> spp.; not pathogenic to banana; renamed <i>Fusarium oxysporum</i> f. sp. <i>heliconiae</i>	Ploetz (2006); Edel-Hermann & Lecomte (2019)
R4TR4/STR4	Strongly harmful to Cavendish (e.g., Grand Naine, Williams, Valery); cultivars susceptible to STR4/R2/R1 often also susceptible to TR4; TR4 threatens multiple <i>Musa</i> sections	Ploetz <i>et al.</i> (2015); García-Bastidas (2019); Pérez-Vicente <i>et al.</i> (2014); Cheng <i>et al.</i> (2020)

Race 4 is further subdivided into Tropical Race 4 (TR4) and Subtropical Race 4 (STR4).

1940). Nomenclature evolved as the concept of *formae speciales* was formalized by Snyder and Hansen, building on earlier work by Wollenweber & Reinking (1935) and Snyder & Hansen (1940). Since 1940, the *Fusarium* species responsible for banana wilt has been classified as *F. oxysporum* f.sp. *cubense*. Foc produces three asexual spore types. Larger, thin-walled macroconidia typically form on the surface of infected tissues; microconidia are also produced, and older hyphae generates spherical, thick-walled chlamydospores (Wardlaw, 1961). As a soil-borne pathogen, Foc grows as hyphae in organic residues and forms chlamydospores with prolonged survival potential. It can invade and persist as an asymptomatic endophyte in a range of non-host plants, complicating management in soil and colonized host debris (Pittaway *et al.*, 1999; Hennessy *et al.*, 2005). Four races of Foc are delineated by differential pathogenicity on banana cultivars as shown in Table 1.

Recent molecular studies have revealed substantial phylogenetic and pathogenic diversity within the *F. oxysporum* species complex, challenging earlier race-based classification systems. While traditional studies relied on pathogenicity assays and vegetative compatibility groups (VCGs), modern approaches such as multilocus sequence typing (MLST), amplified fragment length polymorphism (AFLP), and whole-genome sequencing have uncovered extensive cryptic diversity that is not captured by race designations alone (Maryani *et al.*, 2019; Ordóñez, 2018). These methodological advancements have refined our understanding but also exposed inconsistencies in how races are delimited and how virulence is predicted across environments. For instance, while TR4 isolates are genetically distinct from Subtropical Race 4 (STR4), overlapping pathogenicity on Cavendish cultivars has complicated diagnostic interpretation (Ploetz, 2015; García-Bastidas, 2019, 2022). This taxonomic uncertainty has significant implications for quarantine and surveillance, as diagnostic assays developed for one lineage may not accurately detect emerging variants or recombinant strains. Another critical methodological challenge lies in distinguishing between endophytic and pathogenic phases of *F. oxysporum* in banana roots. Current diagnostic assays often detect the pathogen's presence but fail to differentiate between latent infection and active disease (Pegg *et al.*, 2019). This limitation can lead to false positives in early surveillance, affecting containment strategies. Similarly, inconsistencies among PCR-based assays—targeting rDNA, translation elongation factor (TEF-1 α), or secreted in xylem (SIX) genes—underscore the need for validated, standardized molecular protocols (Dita *et al.*, 2018; Pant *et al.*, 2023). Despite major progress, significant research gaps persist. These include

the incomplete global mapping of VCG diversity, limited understanding of host–pathogen interactions in resistant cultivars, and insufficient field-level validation of molecular diagnostic tools under tropical conditions. Furthermore, Nepal-specific isolates have not yet been characterized genomically, leaving uncertainties about whether they align with the dominant Asian TR4 clade or represent new introductions (Pant *et al.*, 2023).

HISTORY

Understanding the historical evolution of *Fusarium oxysporum* f. sp. *cubense* (Foc) is central to tracing how the pathogen adapted, spread, and shaped modern banana production systems worldwide. *Fusarium oxysporum* f.sp. *cubense* (Foc)—a member of the *Fusarium oxysporum* species complex—has been associated with banana wilt since 1910. E.F. Smith coined the epithet “cubense” after isolating the pathogen from diseased plants in Cuba (Smith, 1910). In 1935, H.W. Wollenweber and O.A. Reinking recognized it as a variant of *Fusarium oxysporum*. Field observations of banana wilting predate formal naming: the disease was reported in Australia in 1876 (Bancroft, 1876), with notable outbreaks on Gros Michel plantations in Costa Rica and Panama by 1890 (Stover, 1962). The impact on Gros Michel was devastating, contributing to that cultivars near extinction across major producing regions (Pérez-Vicente *et al.*, 2014). Even in the absence of a host, this resilient pathogen can persist in the soil for many decades. The commercial transition to Cavendish cultivars—largely resistant to races 1 and 2—stabilized production for decades. However, this shift also created genetic uniformity, making the global banana industry inherently vulnerable to new pathogen variants (Ploetz, 2006). That equilibrium shifted with the emergence of Race 4, particularly Tropical Race 4 (TR4), against which Cavendish and multiple other cultivars are vulnerable; the dominance of Cavendish has magnified industry-wide risk (FAOIPPC, 2022). By the early 1990s, TR4 had spread across Asia, reshaping trade patterns, research priorities, and phytosanitary protocols (Dita *et al.*, 2018). The pathogen's ability to remain viable in soil for more than 20 years, infect through root injuries, and evade chemical control options underpins its designation as the most significant menace to banana cultivation (Ploetz, 2009). Early assessments already warned of extensive vulnerability and likely further spread (Ploetz, 2006). From a research standpoint, historical outbreaks have influenced methodological advances—from early morphological identification to race typing and, more recently, molecular and genomic diagnostics (Maryani *et al.*, 2019). Despite these advances, com-

parative historical analyses remain limited; most records focus on descriptive accounts rather than understanding how pathogen evolution and cultivar transitions shaped present vulnerabilities.

DISTRIBUTION AND EPIDEMIOLOGY

Genetic diversity in *Musa* is concentrated in Southeast Asia, and TR4 is commonly hypothesized to have co-evolved there (Buddenhagen, 2009). Alternative views propose multiple origins, both within and beyond the *Musa* center of diversity (Bentley et al., 1998). Confirmed incursions outside Southeast Asia include outbreaks in Jordan, Mozambique, Lebanon, Oman, and Pakistan (Ordoñez, 2015). More recent detections have extended its confirmed presence to Colombia, Laos, and Myanmar (Dita et al., 2018; FAO TR4 Global Network, 2025). The precise transcontinental pathways remain uncertain. Given the distances involved, long-range spread is unlikely to be explained by infected suckers alone and more plausibly reflects human-mediated transport of contaminated soil, plant material, or agricultural goods, including asymptomatic tissue-cultured plants and nursery equipment (Stover, 1962; Pérez-Vicente et al., 2014). Evidence from genomic tracing suggests multiple introductions rather than linear diffusion, underscoring the role of trade and labor mobility in cross-border transmission (García-Bastidas, 2019). At local and farm scales, soil-borne inoculum moves primarily where roots contact one another; infections in short-lived secondary and tertiary roots release propagules into surrounding soil (Stover, 1962). Movement of planting material remains a dominant driver of new foci (Stover, 1962; Pérez-Vicente et al., 2014), while labor exchange between farms accelerates spread (Viljoen et al., 2020). Suckers taken from infected mother plants may remain symptomless for extended periods, enabling latent infection (Stover, 1962). Natural dispersal also occurs via rain splash and erosion; recent microcosm experiments confirm that macroconidia can survive and disperse in water and sediment, extending risk to irrigation networks (Wen et al., 2015). Additional carriers include banana weevil adults, which can externally transmit TR4 propagules (Ploetz et al., 2015; Pegg et al., 2019), along with domestic animals and human movements near infected plantations (Australian Government Department of Agriculture, Fisheries and Forestry, 2023). Following initial introduction, secondary dissemination is dominated by contaminated soil, water, and plant debris moved by vehicles, irrigation, or surface runoff (Dita et al., 2018). Spores can survive in soil and plant waste for decades (Stover, 1962; Ploetz, 2006), with chlamydospores remaining viable for more than 30 years under conducive moisture and temperature regimes (Buddenhagen, 2009). However, significant epidemiological gaps persist. Few studies have quantified inoculum thresholds for infection under subtropical or highland conditions, and spatially explicit risk models remain underdeveloped for South Asia. In Nepal, systematic mapping of TR4 presence, environmental correlates, and soil survival dynamics is yet to be initiated, limiting preparedness.

SYMPTOMS OF THE DISEASE

Infection initiates at the roots: conidia germinate, hyphae adhere to the epidermis, penetrate the cortex, and enter xylem vessels, where the pathogen proliferates and moves acropetally (Pérez-Vicente et al., 2014). Vascular colonization leads to discoloration and physical occlusion of vessels, interrupting water transport and precipitating wilt (García-Bastidas, 2022). Additional dysfunction arises from toxin production and host responses—Tyloses and gums—that further restrict flow; these defenses form earlier and more rapidly in resistant than in susceptible cultivars (Ploetz et al., 2015). Major roots and rhizomes are seldom invaded directly; rather, infections arise via primary/secondary root exudates and subsequent entry through fine roots (Stover, 1962). External symptom expression is influenced by cultivar, environment, and inoculum load. In Cavendish bananas, symptoms typically develop 4–5 months after planting, though earlier onset (within two months) occurs if infected suckers are used. In cooler or drier soils, latent infections may remain symptomless for several seasons before activation under favorable conditions (Pegg et al., 2019). Early foliar symptoms begin with marginal chlorosis on the oldest leaves, progressing to necrosis and midrib splitting. As disease advances, leaves collapse along the petiole, producing a skirt-like appearance of hanging necrotic leaves—a diagnostic hallmark of Fusarium wilt (Dita et al., 2018). Internal symptoms are equally characteristic. Longitudinal sections of the rhizome or pseudostem show reddish-brown to dark-purple vascular streaking, often radiating outward from the central cylinder (Stover, 1962; Ploetz, 2006). The vascular discoloration may intensify toward the collar region, and in severe cases, the corm becomes desiccated and fibrous with a distinct foul odor due to secondary microbial colonization. Because Cavendish cultivars are resistant to Foc Race 1, wilt in Cavendish plantations is a strong indicator of TR4. However, field diagnosis based solely on visual symptoms can be unreliable, as early TR4 manifestations resemble those caused by nutrient deficiency, drought stress, bacterial corm rot (*Erwinia* spp.), and “false Panama” wilt (Australian Government Department of Agriculture, Fisheries and Forestry, 2023). TR4 does not discolor fruit, distinguishing it from Moko disease (*Ralstonia solanacearum*) and Banana blood disease (*Ralstonia syzygii* subsp. *celebesensis*), both of which infect fruit pulp and peduncle tissues (Plant Health Australia, 2013). Recent observations also suggest that symptom progression varies with water regime, soil type, and temperature, as anaerobic or saturated soils intensify vascular decay (Wen et al., 2015). Additionally, asymptomatic infections in roots and corms detected by PCR highlight the need for molecular confirmation even when external signs are absent (Dita et al., 2018; Pant et al., 2023). Field images provided illustrate typical canopy yellowing, leaf collapse, and basal pseudostem necrosis in advanced cases (Figure 1a–1c).



Figure 1.a



Figure 1.b



Figure 1.c

Figure 1a: Advanced wilt with necrotic leaf "skirt"; **Figure 1b:** Young plant showing petiole collapse and early wilt; **Figure 1c:** Scattered symptomatic plants with marginal chlorosis (Photo taken by Dipendra Dhakal, Panama wilt survey (Kailali, Nepal).

MANAGEMENT AND CONTROL OF PANAMA DISEASE TR4

Management of *Fusarium oxysporum* f. sp. *Cubense* Tropical Race 4 (Foc TR4) has focused on chemical and biological options, cultural manipulation of, and resistance breeding. However, the pathogen's ability to persist in soil and plant debris for long periods severely limits cultural tactics such as crop rotation (Brandes, 1919). Repeated chemical interventions (e.g., corm injection and soil drenches with carbendazim) raise environmental concerns and have not delivered sustainable control (Getha & Vikineswary, 2002). Consequently, in areas still free of TR4, exclusion is the principal strategy—preventing entry through strict hygiene, regulated movement of planting material, and targeted awareness—supported by readiness and accurate diagnostics (Dita et al., 2018). Once TR4 is introduced, eradication is rarely feasible, and containment becomes the priority. Immediate measures include rigorous sanitation to minimize secondary spread: cleaning footwear, tools, machinery, and vehicle wheels that contact infested ground; and disinfecting implements between suspect and confirmed plants during roguing operations (Dita et al., 2018). Disinfectants used for decontamination include formaldehyde and quaternary ammonium compounds (Nel et al., 2006; Meldrum et al., 2013). These practices should be embedded in farm protocols and enforced across neighboring fields to reduce farm-to-farm transmission. At national and industry levels, prevention remains the most lever. Foc TR4 should be listed on the quarantine pest roster; imports of *Musa* plants and other known hosts from TR4-affected countries should be prohibited or tightly regulated. Any *Musa* germplasm or propagative material entering the country must pass through intermediate

quarantine, be properly indexed, and be certified free of Foc TR4. Early detection relies on structured surveillance techniques (e.g., field surveys) and clearly designated diagnostic capacity—NPPO reference laboratories determine where Foc TR4 can be confirmed (Pérez-Vicente et al., 2014). Maintaining an up-to-date roster of national and international experts facilitate rapid confirmation and response planning when incursions are suspected (Pérez-Vicente et al., 2014).

Cultural control

Cultural measures aim to prevent introduction and contain secondary spread once *Fusarium oxysporum* f. sp. *cubense* TR4 is present. On their own they rarely eradicate the pathogen because TR4 persists in soil and plant debris, but—when rigorously implemented and paired with clean planting material and surveillance—they materially reduce farm-to-farm transmission (Stover, 1962; Herbert & Marx, 1990; Buddenhagen, 2009; Hermanto et al., 2012; Dita et al., 2018). In several producing regions (e.g., the Philippines, Indonesia), burning rice hull is used as a fire-based soil sanitation practice (Molina et al., 2010). Other soil treatments such as solarization, methyl-bromide fumigation, and water inundation can temporarily depress inoculum but typically for only a single fruiting cycle because TR4 rapidly recolonizes treated zones (Stover, 1962; Herbert & Marx, 1990; Hermanto et al., 2012). Rotation effects are inconsistent in perennial bananas; alternating Cavendish with other cultivars may reduce disease pressure locally but does not eliminate inoculum reservoirs (Buddenhagen, 2009). Additional on-farm strategies emphasize proper drainage design, raised beds, and soil structure improvement to minimize waterlogging, which favors chlamydospore survival (Stover, 1962; Dita et al., 2018). Maintaining vegetation buffers and grassed waterways helps intercept soil particles carrying inoculum and reduces the hydrological spread of TR4 (Pegg et al., 2019). Deep plowing and fallowing infested sites for extended periods—combined with removal of alternative hosts—can lower pathogen load and delay reinfestation (Buddenhagen, 2009; Hermanto et al., 2012). Composting infested residues at high temperature before field reuse is also encouraged to prevent inadvertent reintroduction (Dita et al., 2018).

At the field scale, the strongest evidence base supports hygiene protocols that interrupt soil and water movement. Core actions include restricting entry; managing footwear and clothing; installing designated clean-down areas for tools, machinery, and vehicle wheels; and avoiding shared equipment between blocks. Practical standards specify pre-cleaning to remove soil, followed by disinfection using approved solutions, footbaths at entry/exit points, and containment of wash-down residues to prevent re-contamination (Biosecurity Queensland, Department of Agriculture and Fisheries, 2016). These measures are complemented by zoning (separating infested, suspect, and clean areas), traffic control (one-way farm traffic, dedicated lanes), and water management to prevent movement of contaminated runoff or irrigation water into clean blocks (Altendorf, 2019; Pegg et al., 2019). Frequent inspection of water sources

and maintaining physical barriers between drainage systems of infested and clean fields are increasingly recognized as cost-effective preventive steps. Training workers to identify suspect plants, record movements, and follow roguing protocols (bagging tools; disinfecting between plants) is essential to reduce within-farm spread (Dita *et al.*, 2018; Pegg *et al.*, 2019). Where outbreaks occur, containment relies on rapid roguing and biosecurity cordons rather than curative treatments. Infested plants (including mats and immediate satellites) should be isolated and removed under strict tool/footwear disinfection; movement of soil, planting material, and organic debris off-site must be prohibited (Dita *et al.*, 2018). Because eradication is rarely achievable in perennial systems with latent infections, authorities and growers prioritize long-term exclusion of TR4 from unaffected farms through certified, indexed planting material, documented sanitation, and periodic surveillance (Dita *et al.*, 2018; Pegg *et al.*, 2019).

Biological control

Biological control offers a lower-risk alternative to broad-spectrum fungicides and can complement exclusion, sanitation, and certified planting material. Nevertheless, durable field performance against Foc TR4 remains inconsistent (Ploetz, 2015). Trials have evaluated diverse agents in glasshouse and field conditions. Endophytic and rhizosphere bacteria/fungi show the most promise: *Bacillus licheniformis* has produced positive outcomes, while the root-colonizing fungus *Serendipita indica* (formerly *Piriformospora*) has demonstrated antagonism to TR4 (Cheng *et al.*, 2020; Li *et al.*, 2021). In China, well-characterized antagonists applied alone or with bio-organic fertilizers (BIOs) to steer the rhizosphere microbiota have suppressed disease and improved plant vigor (Shen *et al.*, 2015; Xue *et al.*, 2015; Shen *et al.*, 2019). A marine-derived *Streptomyces* sp. (WHL7) has also emerged as a candidate BCA against TR4 (Wang *et al.*, 2022). Across agents, however, multi-year banana systems tolerate less yield loss than short-season crops; annual losses of 10–20%—acceptable in vegetables—are not sustainable in bananas (Ploetz, 2015). Additional studies have highlighted the potential of combining antagonistic microorganisms such as *Trichoderma*, *Streptomyces*, and *Bacillus* spp. with organic soil amendments to enhance suppressiveness and restore soil microbial balance (Shen *et al.*, 2015; Bubic *et al.*, 2019; Wang *et al.*, 2022). Compost- or biochar-based carriers have shown to improve microbial persistence and competitive colonization in the banana rhizosphere (Xue *et al.*, 2015; Shen *et al.*, 2019). Integrating biologicals with cover crops or green manures has also been observed to modify the nematode–microbe food web, indirectly suppressing *Fusarium* inoculum and enhancing soil health (Dita *et al.*, 2018). Field-scale success appears to depend on consortia and microbiome conditioning rather than single antagonists. BIOs combined with pre-treatments (e.g., ammonia fumigation) have reduced Panama disease by ~55% and promoted growth (Shen *et al.*, 2019). Bubic *et al.* (2019) synthesized >180 studies and reported field control up to ~70–79% with *Trichoderma*/*Pseudomonas* and selected endophytes, with generally lower effects for *Bacillus* spp. and

arbuscular mycorrhizae. Further evidence suggests that co-application of BCAs with resistant cultivars or tissue-culture seedlings enhances establishment and delays symptom expression (Pegg *et al.*, 2019; Li *et al.*, 2021). However, adoption in smallholder systems remains limited by inconsistent formulation quality, short shelf life, and variable farmer compliance. Despite these advances, replication across sites and seasons remains limited, and scalability hinges on formulation stability, colonization under farmer conditions, and integration with hygiene and water management.

Chemical control

Conventional chemical and physical measures have shown limited or inconsistent efficacy against TR4 (Ploetz, 2015). Early work found some activity for potassium phosphonate (Herbert & Marx, 1990), and subsequent assays reported mycelial growth or symptom reduction with prochloraz and propiconazole, including as root-dip treatments (Nel *et al.*, 2006; Anderson & Aitken, 2021). Additional studies noted partial effects of benomyl and demethylation inhibitors (Nel *et al.*, 2006), while *in vitro* screens identified complete inhibition at low ppm for mixes such as tebuconazole/trifloxystrobin (Nativo), fluopyram/tebuconazole (Luna), and tebuconazole alone (Chand & Singh, 2021). Yet, field-level control remains unreliable, cost-intensive, and environmentally burdensome; no curative or prophylactic fungicide is currently recommended for sustainable management (Ploetz, 2015). Some studies have explored pre-plant chemical dips, soil drenches, and systemic fungicides in combination with biological inoculants or organic matter to improve efficacy (Nel *et al.*, 2006; Shen *et al.*, 2019). However, while these integrated chemical–biological approaches can transiently suppress inoculum loads, their effect diminishes after a few cropping cycles (Dita *et al.*, 2018). Soil fumigants such as methyl bromide, chloropicrin, and formalin have also been trialed but are no longer recommended due to their toxicity, phytotoxicity, and limited long-term suppression (Stover, 1962; Herbert & Marx, 1990; Ploetz, 2015). Nutrient and soil amendments can modulate disease pressure. Silicon (Si) consistently reduced *Fusarium* wilt symptoms in greenhouse banana trials (Gu *et al.*, 2020). N form and rate also matter—nitrate nutrition tends to lessen disease severity, whereas ammonium can exacerbate it (Ploetz, 2015; Dita *et al.*, 2018; Gu *et al.*, 2020; Orr *et al.*, 2022). Combined applications of silicon and calcium-based materials have shown synergistic effects in enhancing structural defense and reducing vascular colonization by TR4 (Peng *et al.*, 1999; Gu *et al.*, 2020). Organic soil amendments, lime, and biochar also enhance soil suppressiveness and indirectly strengthen plant defense through improved microbial activity and nutrient balance. Calcium sources (e.g., CaCO₃, Ca(OH)₂, CaSO₄) may suppress chlamydospore germination and reduce disease without markedly altering soil pH (Peng *et al.*, 1999). In practice, chemical inputs are best positioned as adjuncts to prevention, quarantine, sanitation, and clean planting material rather than as stand-alone solutions for TR4.

FUSARIUM WILT IN NEPAL AND INCURSION OF RACE TR4

Nepal's banana sector is highly exposed to Tropical Race 4 (TR4), as widely grown cultivars are susceptible, and farms rely on informal planting-material channels. FWB-like outbreaks were recorded in Chitwan in 2017 with reported incidences of 30–90% across Malbhog-growing districts (Kema et al., 2021), and Malbhog's extreme susceptibility prompted many growers to abandon the cultivar (Beckman, 1987). Regional signals heightened concern: TR4 had been confirmed in neighboring India (Bihar/Uttar Pradesh) by 2019 (Damodaran et al., 2019), after earlier confirmations across West and South Asia—Pakistan and Lebanon in 2015 (Ordoñez, 2015), Oman and Jordan in the mid-2010s, and Israel in 2016 (Meldrum et al., 2013). Beyond Asia, the first Latin American detection in Colombia (2019) triggered national emergency measures (Altendorf, 2019). Collectively, these incursions delineate a widening regional risk envelope for Nepal tied to trade, labor, and planting-material movements. Countries have responded with progressively stricter biosecurity once TR4 is detected. Australia's 2015 incursion in North Queensland prompted a long-running, state-led program with control zones, movement restrictions, and intensive on-farm hygiene and surveillance (Australian Government Department of Agriculture, Fisheries and Forestry, 2023; Biosecurity Queensland, Department of Agriculture and Fisheries, 2016). Similar approaches—tightened certification of planting material, traceability, and farm zoning—have been adopted elsewhere (Altendorf, 2019). These experiences consistently show that eradication is rare; durable containment depends on early case-finding, rapid roguing under tool/vehicle decontamination, traffic and water management, and sustained compliance audits. In Nepal, the Nepal Agricultural Research Council (NARC) reported TR4 detection from sample testing in Tikapur, Kailali, in August 2023, with early media briefings citing 60–65% infection in surveyed plants (ShareSansar, 2023). Government teams initiated preliminary surveys and diagnostics to delimit affected sites and plan responses (Shrestha, 2023). In the near term, Nepal's priorities mirror lessons from other countries: (i) rapid confirmation and mapping of foci through NPPO-designated labs; (ii) movement controls on planting material, soil, and equipment; (iii) farm-level biosecurity (clean-down points, zoning, traffic control, water/runoff management); and (iv) transition to indexed, certified planting stocks coupled with targeted extension to smallholders.

THREATS OF TROPICAL RACE 4 (TR4) TO NEPAL'S BANANA INDUSTRY

Nepal's banana sector is dominated by susceptible cultivars and informal planting-material flows, leaving farms highly exposed to TR4 incursions in its orchards. Recent statistics indicate the crop's growing economic footprint: FAOSTAT reports ~318 thousand tons of bananas produced in 2022 (national rank ~40s among producers), underscoring the potential scale of impact if TR4 becomes widespread (Helgi Library, 2024). District-level

studies in major production hubs (e.g., Chitwan, Kailali) show bananas as an important cash crop for smallholders and local value chains (Adhikari et al., 2022; Bhatta et al., 2023). Given the absence of widely adopted resistant varieties, sustained disease pressure could depress yields, erode farm incomes, and raise consumer prices while shifting demand to imports. Experiences from other regions illustrate both the pace of spread and the management burden. After first reports across West and South Asia (Pakistan, Lebanon, Oman, Jordan) in the mid-2010s, Latin America confirmed TR4 in Colombia (2019), Peru (2021) and Venezuela (2023), prompting emergency responses and long-term containment programs (Ordoñez, 2015; Altendorf, 2019; Martínez-de la Parte, 2023; Munhoz et al., 2024). Australia's 2015 detection in North Queensland led to a multi-year control program with movement restrictions, zoning, hygiene audits, and industry co-management (Queensland Government – Department of Agriculture and Fisheries, 2025). Global coordination led by IPPC and FAO highlights the principal pathways—infected planting material; contaminated soil on footwear, tools, machinery; irrigation and floodwaters—and stresses that eradication is rare, so early detection plus rigorous biosecurity are decisive (IPPC, 2023; FAO TR4 Global Network, 2025). For Nepal, the threat is immediate and actionable. Following the 2023 field detection in Tikapur (Kailali), priorities are to: (i) delimit and map foci through NPPO-designated diagnostics; (ii) institute movement controls on planting material, soil and equipment; (iii) operationalize on-farm biosecurity (clean-down points, traffic and water/runoff management, tool/boot disinfection); and (iv) accelerate access to indexed, certified planting stocks and extension packages for smallholders—drawing on Australia's surveillance/clean-down standards and FAO/IPPC technical guidance (Biosecurity Queensland, Department of Agriculture and Fisheries, 2016; Altendorf, 2019; Queensland Government – Department of Agriculture and Fisheries, 2025; IPPC, 2023). Aligning these measures with Nepal's production geographies and cross-border trade patterns can mitigate yield losses and protect livelihoods while longer-term breeding and resistant-variety pipelines mature.

Conclusion

Tropical Race 4 (TR4) of *Fusarium oxysporum* f. sp. *cubense* represents a global phytosanitary emergency and an emerging national threat to Nepal's smallholder-based banana sector. This review reveals that TR4's persistence in soil, broad host range, and multiple transmission routes—through contaminated planting material, soil, water, and human activities—make curative approaches unfeasible. Experiences from affected countries confirm that containment, not eradication, is the only realistic goal. Successful management depends on disciplined biosecurity, strict field sanitation, rapid roguing, and adoption of certified, disease-free planting materials. In Nepal, where Cavendish cultivars dominate and informal propagation systems prevail, these vulnerabilities elevate the risk of widespread establishment. The synthesis identifies three immediate priorities for Nepal as

enhancing NPPO-led diagnostic capacity and early-warning surveillance; strengthening farm-level biosecurity measures such as clean-down stations, traffic and runoff management, and quarantine of infected fields; and scaling access to indexed, certified planting material through formal seed-system reform. While cultural, chemical, and biological approaches offer partial suppression, long-term resilience depends on integrating hygiene-based prevention, resistant variety development, and coordinated stakeholder action. Sustained collaboration among researchers, regulators, and growers—supported by transparent data and continuous extension—will be crucial to limit TR4's spread, protect smallholder livelihoods, and preserve the productivity of Nepal's banana value chain.

ACKNOWLEDGEMENTS

We thank our parents for their unwavering support. We are also grateful to Dipendra Dhakal, Sandip Regmi, Jesish Ojha, Bibash Chaulagain, and Pramod Gyawali for their constructive feedback and encouragement throughout the writing of this review.

DECLARATIONS

Author contribution statement: Conceptualization, methodology: A.P., N.D., and S.K.; Investigation: A.P., S.K, and P.P.; Writing -original draft preparation: A.P., S.K and P.P.; Writing-review and editing: A.P, P.P., S.K., and S.K. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest: The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Ethics approval: This study did not involve any animal or human participant and thus ethical approval was not applicable.

Consent for publication: All co-authors gave their consent to publish this paper in AAES.

Data availability: The data that supports the findings of this study are available on request from the corresponding author.

Supplementary data: No supplementary data is available for the paper.

Funding statement: No external funding is received for this study.

Additional information: No additional information is available for this paper.

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