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Integrated pest and disease management for banana crops in East and Central Africa: addressing the challenges of co-occurring biotic threats

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Smallholder subsistence farmers dominate banana (*Musa* spp.) production across East and Central Africa, yet their yields are constrained by a suite of co-occurring biotic threats. Three major diseases, *Xanthomonas* wilt (XW), *Fusarium* wilt (FW), and banana bunchy top disease (BBTD) threaten productivity. These are compounded by two established pests (black weevil, plant-parasitic nematodes) and an emerging pest (banana thrips). Integrated pest and disease management (IPDM) protocols aim to mitigate these challenges by coupling disease-specific interventions with broader agronomic practices. While individual IPDM packages share core components, including biosecurity, accurate diagnosis, roguing, clean planting material, resistant cultivars, vector avoidance, and judicious chemical control, their efficacy can be compromised when multiple threats coexist. Synergistic or antagonistic interactions may arise under these conditions. Part 1 of this review synthesizes current literature on the core components of IPDM strategies for these six biotic stresses, highlighting commonalities and divergences among the recommended packages. In Part 2, it further evaluates the role of standard cultural and agronomic practices in disease-pest management outcomes. These include crop diversification, weed management, planting density, sucker and leaf removal, tillage, mineral and organic fertilization, biocontrol, mulching, pest suppression, and irrigation. By identifying compatibilities and incompatibilities in management when biotic constraints co-occur, and by addressing knowledge gaps across the various protocols, the review provides actionable insights for designing holistic extension programs that harmonize prevention and control measures. As such, IPDM programs should be better equipped to avoid unintended trade-offs and enhancing resilience in banana systems where these threats co-occur.

KEYWORDS

banana bunchy top disease, *Fusarium* wilt, IPDM, *Musa* spp., nematodes, thrips, weevils, *Xanthomonas* wilt

Introduction

Smallholder subsistence farmers dominate the cultivation of bananas (*Musa* spp.) in East and Central Africa (ECA) (Karamura et al., 1998; Tinzaara et al., 2018). Banana is a primary crop critical for household food security. It also serves as a major source of income and one of the region's main cash crops (Abele et al., 2007; Scott, 2021). However, pests and diseases severely constrain banana productivity, causing significant yield losses (Tinzaara et al., 2018). Three major banana diseases impact production in the ECA region: Xanthomonas wilt of banana (XW; Blomme et al., 2023), banana Fusarium wilt (FW; Ploetz, 2015), and banana bunchy top disease (BBTD; Niyongere et al., 2012). Additionally, two established pests, black weevils (Bakaze et al., 2022) and plant-parasitic nematodes (PPN; Coyne et al., 2018), along with an emerging pest, banana thrips (personal communication, Walter Ocimati), adversely affect production in the area.

XW, caused by the bacteria *Xanthomonas vasicola* pv. *musacearum* (Xvm; Aritua et al., 2008; Studholme et al., 2020), is currently the most important and widespread banana disease across ECA (Blomme et al., 2017b). The spread of Xvm is mediated by insect vectors moving between the inflorescences of banana plants, contaminated garden tools, and infected planting material (Ploetz, 2015). The bacteria infect and colonize the plant's vascular system. This infection causes yellow ooze to accumulate in the pseudostem, leaf petioles and midrib tissues (Figure 1A). Consequently, the plants exhibit leaf yellowing and wilting, uneven and premature bunch ripening, and fruit pulp discoloration (Figure 1B) (Tripathi et al., 2009; Ocimati et al., 2013a).

FW is caused by the soil-borne fungus *Fusarium oxysporum* f. sp. *cubense* (Foc). The pathogen infects the roots of banana plants and blocks the vascular system, causing wilting and eventual plant death (Figures 1C, D) (Ploetz, 2015; Dita et al., 2018). The fungus can persist for many decades in infected fields, in the form of chlamydospores in the soil (Pegg et al., 2019). It also survives as an endophyte in alternative host plants, such as weed species (Hennessy et al., 2005; Olivares et al., 2021). Foc is spread via infected planting material as well as spore-infested soil and water (Pegg et al., 2019). Foc is classified into races (R1, R2 and R4) depending on banana cultivar susceptibility (Buddenhagen, 2009; Ploetz, 2015). Foc R1 and R2 are widespread throughout the ECA region (Karangwa et al., 2018). However, they do not affect the most popular cultivars in the region, namely the East African Highland bananas (EAHBs) and African plantains (Molina et al., 2016; Ndayihanzamaso et al., 2020). Nevertheless, within the diverse banana production landscapes, other cultivars remain vulnerable. These include dessert banana types (e.g., AAA Gros Michel and AAB Sukari Ndizi or Apple banana), ABB beer banana types (e.g. Pisang Awak) and ABB cooking types (e.g. Bluggoe). Foc Tropical Race 4 (TR4) represents one of the greatest threats to the banana sector worldwide (Dita et al., 2020; Ploetz, 2021). Currently, it is not yet present in ECA. However, its presence in northern Mozambique poses a potential threat to the entire region (Viljoen et al., 2020).

BBTD, caused by the banana bunchy top virus (BBTV; *Babuvirus musae*, family *Nanoviridae*; Dale, 1987), is confirmed in most of ECA (Niyongere et al., 2012; Ocimati et al., 2021b;

Shimwela et al., 2022). The virus is spreading continuously across the region (Simbare et al., 2020; Ocimati et al., 2024; Mahuku and Kumar, 2023; Gaidashova et al., 2025). BBTV is transmitted via infected planting material and by its insect vector, the banana aphid (*Pentalonia nigronervosa*) (Kumar et al., 2011). BBTD leads to substantial yield losses. Early infections inhibit fruiting, while later infections result in distorted, unmarketable fruit (Figures 1E, F) (Hooks et al., 2008).

PPN are critical banana pests. The burrowing nematode (*Radopholus similis*) is generally the most important nematode for *Musa* cultivation due to its distribution, incidence, and aggressive nature (Coyne et al., 2018). Other PPN include root lesion nematodes (*Pratylenchus goodeyi* and *Pratylenchus coffeae*) and the spiral nematode (*Helicotylenchus multicinctus*) (Coyne et al., 2006). These nematodes are all migratory endoparasites (Speijer and De Waele, 1997), though they exhibit different parasitic modes (Quénéhervé, 2009). Sedentary endoparasitic nematodes that feed on banana roots include the root-knot (*Meloidogyne* spp.) and reniform (*Rotylenchulus reniformis*) nematodes (Wang et al., 2016a). Furthermore, nematode species rarely occur in isolation, and complex infections involving multiple species occur regularly (Quénéhervé, 2009; Coyne et al., 2018). Parasitic nematodes are generally spread via infected planting material (Daneel and Mbatyoti, 2024). They damage roots, disrupting water and nutrient uptake and weakening plant anchorage (Figures 2A, B). This often leads to toppling, reduced suckering, delayed maturation, reduced bunch size and overall yield reduction (Speijer et al., 1999; Coyne et al., 2018).

Another key pest is the black banana weevil (*Cosmopolites sordidus* Germar). Its larvae feed on corm tissue (Gold et al., 2003; Bakaze et al., 2022). Larval boring reduces nutrient and water uptake and compromises plant stability (Figure 2C). This results in plant loss from snapping and toppling (Figure 2D), lower bunch weight, mat die-off, and shortened plantation life. In ECA, spread persists due to the continuous use of infected planting material by farmers (Gold et al., 2003; Coyne et al., 2010).

Banana rust thrips are becoming an increasingly important biotic constraint in monocropped banana landscapes, such as those in southwestern Uganda. This emergence is causing a substantial impact on fruit quality and marketability (Figures 2E, F), necessitating rapid response. Ongoing research aims to identify the pest, study its spread and impact, and develop integrated prevention and control measures. The diversity appears large in the ECA region (Njue et al., 2025), which may complicate the formulation of management strategies. Although banana thrips have long existed in ECA production landscapes, intensification, monocropping, and climate change appear to have increased population numbers and impact. Walangululu et al. (2010) reported that the fruit peel disease which is occasionally observed in South Kivu Province of eastern DR Congo is initially caused by sap-sucking insects, possibly by thrips. Although no research has yet been published on the recent expansion and impact of this pest in southwestern Uganda, we have included general banana thrips management strategies in our comparison of practices.

Integrated pest and disease management (IPDM) protocols are developed and distributed to smallholder farmers through extension services to combat these threats. For each pest or disease, an

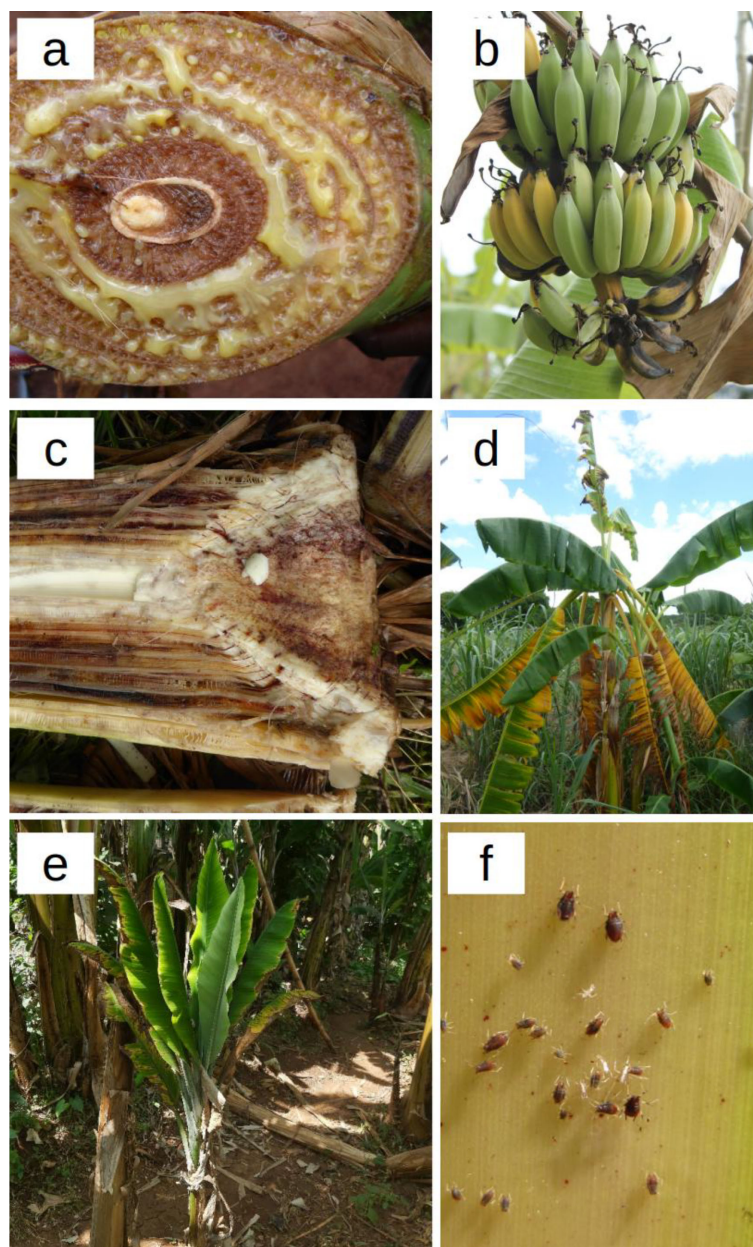


FIGURE 1

Typical symptoms of the banana diseases *Xanthomonas* wilt (**A, B**) respectively depicting bacterial ooze in the pseudostem and premature fruit ripening), *Fusarium* wilt (**C, D**) respectively depicting discoloration of the vascular system in the pseudostem, and yellowing of outer/oldest leaves) and Banana Bunchy Top Disease (**E, F**) respectively depicting the most severe symptom, i.e., bunchy topped leaf appearance, and the aphid vector mediating the spread of BBTV).

integrated approach combines various practices to manage the specific issue, thereby addressing specific host-pathogen interactions (Sileshi and Gebeyehu, 2021). However, focusing on one disease or pest at a time can be insufficient, especially when farmers are facing co-occurring threats, as is common in ECA. Effective IPDM requires educating farmers on critical differences in management practices for various pests and diseases. This ensures they possess the knowledge to apply the required approach. Moreover, a comprehensive IPDM approach aligns prevention and control practices for co-occurring threats. This alignment prevents a solution for one problem from unintentionally exacerbating another.

Each pest and disease generally has a core prevention and control package, supplemented by advice on standard banana field agronomic and cultural practices. The main components of these packages are well-established and are consistently recommended across various institutions' IPDM protocols. However, the impact of cultural practices is often less clear. This uncertainty stems from their varying effectiveness depending on local conditions and environments, as well as differences in application methods. This review examines the current literature to identify recommendations and knowledge gaps for each component of the main management packages and linked cultural practices. It highlights how these components align or differ among the six biotic threats. The goal is to provide guidance for developing

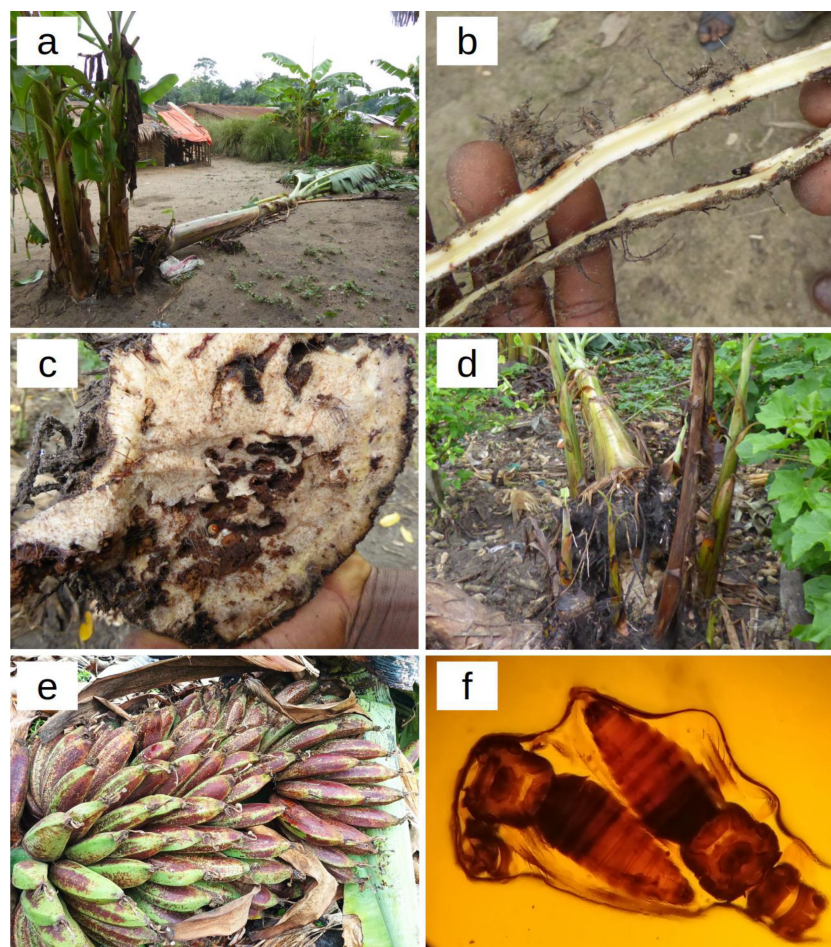


FIGURE 2

Typical symptoms of the pests plant-parasitic nematodes (A, B) respectively depicting a toppled plant and the reddish-brown-black discoloration of an affected root cortex), banana weevil (C, D) respectively depicting banana weevil larvae damage in the corm and plant snapping due to corm weakening) and banana thrips (E, F) respectively depicting a banana bunch severely damaged by banana thrips, and causal thrips under a microscope.

extension programs in regions where these threats co-occur. In the first section, the main IPDM components are compared at a fundamental level across the three diseases and one pest, with a complete overview in [Table 1](#). In the second section, the impact of a wide range of standard agronomic practices for optimal banana cultivation is reviewed in more detail, with a full summary provided in [Table 2](#). An overview of studies assessing the impact of agronomic practices under field conditions is provided in supplementary information.

Part 1. Main IPDM components per disease, and pest

Exclusion through biosecurity and quarantine

The first component of IPDM should be pathogen exclusion. This entails preventing the pathogen from entering healthy areas and fields ([Dita et al., 2018](#)). Exclusion depends on biosecurity measures at various scales, including at national, regional, farm, and

field levels. At national and regional levels, phytosanitary organizations bear this responsibility. They regulate and halt the large-scale movement of infected planting material and soil. Nevertheless, a lack of concrete import certification or phytosanitary regulations at African borders often precludes effective exclusion ([Busogoro et al., 2023](#)). At local levels, communities and farmers play a critical role in exclusion. They ensure the use of clean planting material (see below) from disease-free regions ([Kumar et al., 2015](#); [Blomme et al., 2017b](#)).

Movement of infected planting material is a key mode of spread of each of the investigated banana diseases and pests (FW, BBTD, XW, weevils, nematodes and thrips). Therefore, smallholders across ECA should avoid this practice. In the case of FW, soil contamination with spores further complicates exclusion efforts ([Dita et al., 2018](#)). At the boundaries of large mono-cropped plantations (e.g. in Latin America and Australia), field-level exclusion efforts can include limiting human movement, washing vehicles, disinfecting footwear, and prohibiting the movement of plant material (among other measures; [Munhoz et al., 2024](#)). However, the application of such measures is variable in smallholder settings, due to a lack of financial resources, often limited insights and knowledge about

TABLE 1 Reference table on main IPDM components of key banana diseases and pests for ECA smallholders.

Practice	Xanthomonas wilt (XW)	Fusarium wilt (FW)	Banana bunchy top disease (BBTD)	Thrips	Weevils	Nematodes
Exclusion	Use clean planting material from disease-free regions; avoid moving infected material					
Detection/ Diagnosis	Regular monitoring. Look for sticky yellow ooze from cut stems, premature fruit discoloration	Regular monitoring. Inspect for internal vascular discoloration, and outer leaves wilting like a “skirt”	Regular monitoring. Check for dark green streaks on leaf sheaths. Identify “bunchy cluster” at plant top	Regular monitoring. Use yellow or blue sticky traps and pitfall traps with attractants (effectiveness varies)	Regular monitoring. Trap adults using split pseudostem sections or corm residues.	Regular monitoring. Look for plant toppling. Inspect corm/root for reddish-brown to black lesions
Roguing	SDSR (Single Diseased Stem Removal) for individual stems; CDMU for newly introduced disease	CDMU required (full uprooting including corms). Consider buffer zone. No herbicides.	CDMU required (full uprooting including corms). Consider buffer zone.	Remove severely damaged plant material to eliminate breeding grounds	Remove severely damaged plant material to eliminate breeding grounds.	Remove severely damaged plant material to reduce pest pressure
Debris disposal	Keep removed stems intact (minimize cuts), and heap at field edge to decompose	Deep burial of all infected mat debris (most feasible for smallholders)	Chop pseudostems/leaves, quickly bury in a shallow pit with soil cover; uproot corms, cut these into small sections, put on the soil in a sunny location to dry	Bury in a shallow pit, and cover with a thin layer of soil, or compost waste away from the field	Chop corms/ lower pseudostems into pieces and dry in a sunny location	Dry roots and corm sections in a sunny location and subsequently burn these
Fallowing	Short fallow sufficient after CDMU (6–12 months in intensive systems). Not relevant after SDSR.	Standard fallowing ineffective.	3-month fallow recommended after removing affected mats	Not well documented	Maintain absence of banana hosts for several weeks; effective destruction of old plants critical.	Maintain absence of banana hosts for several weeks; effective destruction of old plants critical.
Clean planting material	Use symptomless suckers at low risk (preferably from disease-free mats); monitor closely	Source from symptomless fields when certified options unavailable	Source from symptomless fields when certified options unavailable	Source suckers from thrip-free fields and mother plants	Treat corms/ suckers: pare roots/outer tissues; submerge in boiling water 20–30 seconds	Treat corms/ suckers: pare roots/outer tissues; submerge in boiling water 20–30 seconds
Cultivar selection	No resistant varieties available. All cultivated bananas in Africa are susceptible.	This is a primary strategy. Use resistant/tolerant varieties tailored to Foc races (Foc R1, R2, TR4).	No durable resistance available; some genotypes show reduced infection rates	No documented resistance or tolerance currently available	Several resistant cultivars available, although cooking/plantain types remain susceptible	Partially resistant germplasm available.
Preventing contact with insect vectors and pests	Remove male buds immediately after last hand forms	Not insect-vectored	Bag inflorescence to prevent aphid contact. Remove old leaves to suppress aphids.	Bag developing bunches with fine-mesh polyethylene bags just as flower bell emerges.	Use traps (split pseudostem or pheromone) to catch adults	Not relevant
Biosecurity/ Phytosanitary	Sterilize tools regularly using soap, detergent, bleach, or fire during field work. Prevent exchange of infected planting material.	Minimize foot traffic; thoroughly clean soil from footwear/tools; dig 50–80 cm deep ditches around plots. Prevent exchange of infected planting material.	Prevent exchange of infected planting material.	Focus on general hygiene and avoiding movement of infested plant material	Focus on general hygiene and avoiding movement of infested planting material	Focus on avoiding movement of infested planting material; always use clean planting materials
Chemical control	No chemical control.	Fungicides show promise in lab but field evaluation needed. Not recommended	No chemical control.	Insecticides available but restricted to severe infestations; cost/ availability barriers	Insecticides available but restricted to severe infestations; cost/ availability barriers	Nematicides available but restricted to severe infestations; cost/availability barriers

TABLE 2 Reference table on supporting field management practices strengthening IPDM of key banana diseases and pests for ECA smallholders.

Agronomic practice	Xanthomonas wilt (XW)	Fusarium wilt (FW)	Banana bunchy top disease (BBTD)	Thrips	Weevils	Nematodes
Crop Diversification	• Mix cultivars (susceptible + tolerant/resistant) to reduce establishment risk. • Avoid alternative hosts. • Pruning leaves to manage shade for intercrops can spread XW via tools.	• Rotate with Allium crops (Chinese chive), pineapple, pepper, or eggplant to suppress spores. • Interplant with Alliums or use cover crops to improve soil microbiome. • Avoid alternative hosts. • Minimize field visits to prevent spore spread. Use cover crops to reduce soil erosion.	• Diversify to reduce banana canopy connectivity. • Use field isolation and border hedges to limit aphid dispersal. • Avoid alternative hosts. • Trap plants for aphids are proposed but not yet proven effective for bananas.	• Limited info for banana thrips. Many thrips species feed on various plant. Diversify cropping systems may alter habitat favorability and encourage natural enemies through diverse vegetation. • Consider trap crops to divert thrips, though field data is limited.	• Intercropping is not a suitable control option for weevils. • Diversify cropping systems may alter habitat favorability and encourage natural enemies.	• Intercropping often introduces associational resistance, effectively suppressing nematode populations. • Use antagonistic or trap crops.
General: • Diversification requires careful species selection. Introducing alternative host can worsen diseases and pests. • Focus on improving the soil microbiome through diverse root exudates potentially combined with organic amendments, which can activate plant immunity and inhibit pathogens. • Be aware of increased management need for intercropping, which can inadvertently spread diseases. Cover crops may be a lower-risk alternative for disease suppression as they require fewer field visits.						
Weed Management	• Remove weeds that serve as alternative hosts (e.g. Canna spp. Weeds). • Disinfect tools after weeding.	• Weed carefully to avoid spreading Foc spores via soil on tools/shoes. • Minimize disturbance of Foc-infected weeds to prevent increased spore production. • Consider leaving some weeds that host beneficial fungal endophytes against Foc TR4. • Clean tools.	• Remove weeds that serve as alternative hosts for BBTV. • Clear dense weeds around banana mats to eliminate humid aphid shelters. • Expose aphids to sunlight and wind by reducing weed cover. • Weed removal may also reduce natural enemy populations of aphids.	• Some weeds may attract specific thrips species (could be used strategically for management). • Weeding reduces overall thrips habitat suitability and host availability.	• Impact unclear	• Prioritize weeding. Many weeds are alternate hosts/reservoirs.
• Complete weed eradication may not be optimal. Some weeds host beneficial microbes that suppress pathogens. • Weed removal may change habitat of vectors and pests, but also reduce predator populations. Balance pest control with beneficial insect conservation. • Understand which local weeds are hosts for specific pests/diseases. • Clean and disinfect tools during weeding activities.						
Planting Density	• Wider spacing may help, but impact may be minimal.	• Use wider spacing to reduce infections.	• Avoid high planting densities to reduce aphid habitats.	• Variable impact: Some species prefer lower densities, others higher.	• Impact unclear	• Avoid dense planting with overlapping root systems.
• Wider spacing reduces disease/pest pressure but may lower total yield per hectare. Find the optimal balance for your farm.						
Removal of excess suckers and leaves	• Suspend de-trashing to prevent tool-mediated spread. (Tool sterilization often inconsistent.) • Suspend de-suckering until no affected plants observed for several months. • Alternatively bend excess leaves by hand or with wooden stick.	• Avoid deleafing and using detached leaves as mulch (increases soil inoculum).	• Deleaf and desucker to reduce aphid habitats and colony build-up. Also during dry seasons.	• No info for banana thrips. Expected: Desuckering or removing selected leaves and flower remnants can reduce habitats.	• Limited evidence • Sanitation practices may decrease weevil damage.	• Limited evidence • Sanitation practices may decrease weevil damage.
• What helps one disease may worsen another. Tailor practices to dominant threats in your area. • If cutting is necessary, sterilize tools thoroughly, but recognize this is often impractical for smallholders. • When cutting is risky, bend leaves at petiole level instead of removing them entirely. • Increased field visits for weeding/pruning can spread diseases. Weigh benefits against risks.						
Tillage	• No specific research on direct impact, but root cutting is a known risk. Limit to superficial tillage in affected fields to avoid cutting roots.	• Avoid or minimize tillage to prevent spore spread and root damage	• No specific research on tillage impact.	• Consider conservation tillage: May reduce numbers for some species. • No specific studies on banana thrips.	• Impact unclear	• Adopt conservation tillage: Improves regulation of parasitic nematodes.

(Continued)

TABLE 2 Continued

Agronomic practice	Xanthomonas wilt (XW)	Fusarium wilt (FW)	Banana bunchy top disease (BBTD)	Thrips	Weevils	Nematodes
	- Shift towards conservation tillage where possible. Tillage causes mechanical damage to roots; consider no-till or minimal-till approaches to maintain root integrity. - Tillage poses high risks for FW (spore movement) and XW (root cutting/tool transfer). Minimize soil disturbance in infected zones.					
Mineral Fertilization	No clear field evidence that fertilization controls XW.	- Avoid high ammonium (NH_4^+) nitrogen. - Prefer nitrate (NO_3^-) forms of nitrogen where available. - Combine organic + inorganic nitrogen for better FW management. - Integrated potassium management (inorganic K + manure + bacteria) may reduce symptoms. - Be cautious with phosphorus.	Limited evidence on fertilizer impact.	- No specific studies on banana thrips yet. - Modifying fertilization has reduced other thrips species.	Impact unclear	Impact unclear
	Many fertilizer-disease/pest relationships lack field validation in ECA.					
Organic Amendments	- Limited evidence on direct impact. - Expected benefit: Enhanced plant performance and natural defense.	- Field trials show reduced FW incidence with organic amendments. - Apply organic amendments (compost, manure, neem cake) to improve soil health.	- Limited evidence on direct impact. - Expected benefit: Enhanced plant vigor and natural defense mechanisms.	- No specific studies on banana thrips yet. - May interfere with thrips life cycle (pupal stage in soil/litter). - Improved soil health may enhance plant resistance to pest pressure.	- No specific studies on direct impact. - Organic amendments could create suitable environment for weevil propagation.	Field trials show suppression of parasitic nematodes.
	- Ensure organic amendment quality. Poor quality materials can undermine disease control effectiveness. - Combine organic amendments with other IPDM practices (diversification, weed management, etc.) for best results. - Primary benefit comes from improved soil structure, nutrient availability, and microbial activity. - Effectiveness varies by amendment type, soil properties, and pathogen/host combinations.					
Biocontrol	Not ready for field use: Research is still in the exploratory phase.	- Biocontrol agents show promise in labs/greenhouses but results vary in the field. - Not yet a standardized, reliable solution for small farms.	Still experimental; not a standard recommendation yet.	- Promising for future biopesticide products but not widely available. - Fungal biopesticides: Specific fungi can induce mortality in thrips while keeping bananas marketable. - Natural enemies: Parasitic wasps and predatory mites help, but impact is often limited.	- Classical biocontrol largely ineffective. - Generalist predators (ants) that attack eggs/larvae are promising.	Available but difficult. Agents exist but field application is notoriously inconsistent.
	Biocontrol is currently not a silver bullet. Field efficacy is often inconsistent compared to lab results.					
Mulching	Limited information available on mulching impact.	- Organic mulches can improve soil health and may have direct fungicidal impact. - Trade-off: Higher weevil densities may increase plant susceptibility to infection. - Limited field trials.	- Limited information on direct impact. - Reflective mulches may deter aphids (based on other species research). - Organic mulches could create favorable humid microclimate for aphids.	- No specific studies on banana thrips yet. - Reflective mulches show potential for deterring thrips. - Organic mulches may reduce thrips by suppressing weeds.	Generally negative impact. Weevil populations higher in mulched plots.	- Tithonia mulch documented to suppress nematodes. - Creates conditions favoring antagonistic soil microbes. - Improved plant health helps even under nematode pressure. - Weevil increase may tip scales to more damage overall.
	- Mulching creates ideal conditions for banana weevils. Weigh this risk carefully before applying. - Mulch type matters. - Consider reflective mulches for thrips/aphid deterrence, though cost may be higher. - Benefits for nematodes/FW may be offset by weevil proliferation. Assess local pest pressures. - Many recommendations lack field validation in ECA contexts.					

(Continued)

TABLE 2 Continued

Agronomic practice	Xanthomonas wilt (XW)	Fusarium wilt (FW)	Banana bunchy top disease (BBTD)	Thrips	Weevils	Nematodes
Control of exacerbating pests	• Manage weevils: They can carry <i>Xvm</i> bacteria and vector disease via corm wounds.	• Control weevils and nematodes: Root/corm damage facilitates <i>Foc</i> infections.	• Not found	• Not found	• Can worsen FW and XW. • Damage is worse when combined with nematodes.	• Can facilitate FW infections. • Damage is worse when combined with weevils.
	• Controlling weevils and nematodes is a critical step in managing FW and XW. • Recognize that weevils and nematodes together cause more damage. Managing one without the other may be insufficient.					
Irrigation	• Impact unclear	• Irrigation facilitates <i>Foc</i> spore movement. • Prevent intake from contaminated areas.	• Impact unclear	• Impact unclear	• Impact unclear	• Impact unclear
	• Water management is a critical control point for FW, although controlling water sources/runoff is often difficult in small-scale systems. Focus on what is manageable (e.g., field drainage). • There is limited evidence linking irrigation to BBTD, thrips, weevils, or nematodes in bananas; rely on proven practices for these threats.					

control practices, and limited practical applicability of control options across production landscapes comprising large numbers of small-holder farms.

Detection and diagnosis

Early detection and diagnosis of diseased banana plants is crucial for identifying effective control strategies. These strategies enable low disease incidence, effective containment, and potential eradication. Early detection relies on regular monitoring, with weekly or bi-weekly intervals generally recommended (Blomme et al., 2017b; Dita et al., 2018). In smallholder settings in ECA, disease diagnosis predominantly relies on symptom recognition. Infected plants of FW, XW, and BBTD each present with characteristic symptoms unique to each disease. For example, XW presents with a sticky yellow liquid oozing out of the cut pseudostem or leaf sheaths, along with premature fruit pulp discoloration. In contrast, FW-infected plants exhibit internal discoloration of the vascular tissue. Additionally, outer leaves gradually wilt and collapse at the petiole, hanging down the pseudostem like a skirt. Initial symptoms of BBTD include dark green streaks on leaf sheaths, petioles and midribs. Later stages involve the formation of a distinctive bunchy cluster at the top of the plant. Nematodes cannot be seen with the naked eye. Therefore, pest detection also relies on symptom observation. Indicators of nematode infestation include plant toppling and distinct reddish-brown to black lesions or rot on the corm and cord roots (Speijer et al., 1999). However, managing multiple diseases and pests can complicate symptom recognition for farmers. Decision-support tools, such as free smartphone applications that detect banana diseases via image recognition (Selvaraj et al., 2019), can support field diagnosis by smallholders.

Monitoring of banana thrips and weevils can be done through trapping. Banana weevils are generally monitored by trapping adults using split pseudostem sections or corm residues (Gold et al., 2003; Bakaze et al., 2022). Regarding thrips, adults emerge from the soil or leaf litter after completing their non-feeding prepupal and pupal stages. During this emergence, pitfall traps

with attractants can be used to capture the adults (Cabrera et al., 2010). However, this method is not always fully effective (Arias de López et al., 2020).

Roguing

Banana plants infected with *Foc*, *Xvm* or BBTV must be removed to prevent pathogen accumulation and spread. Removing severely damaged or dying plant material also aids pest control by eliminating breeding grounds and reducing overall pest pressure (Gold et al., 2003). The destruction of crop residue (pseudostems and/or removal of corms) depends on the specific food sources and breeding sites of the target pest species (Masanza, 2003).

XW is the only one of these diseases for which single diseased stems can be removed from the banana mat (Single Diseased Stem Removal, SDSR; Blomme et al., 2017a). SDSR is feasible because incomplete systemic spread of *Xvm* in banana mats. *Xvm* does not invade all physically connected lateral shoots when one shoot in a mat is infected (Ocimati et al., 2013a, 2015). Complete diseased mat uprooting (CDMU) of XW-infected mats remains recommended in well-managed and market-oriented banana production systems. CDMU is also advised to eliminate inoculum when the disease has recently been introduced to a farm or location (Blomme et al., 2014; 2017a, 2017b). Both BBTD and FW require CDMU (Dita et al., 2018; Omondi et al., 2020), although plant debris disposal methods differ (see next section). BBTV and *Foc* spread systemically throughout a mat. Additionally, *Foc* spores are soil-borne and can infect adjacent plants through their root system. Full uprooting of a BBTD- or FW-infected mat, including all corms, is labor-intensive. However, this practice is imperative to prevent resprouting of diseased plants and pathogen accumulation. Buffer zone creation, the additional removal of mats within a perimeter around affected mats, is sometimes recommended for both BBTD and FW (Kumar et al., 2015; Dita et al., 2018; Omondi et al., 2020). However, this requires removing numerous healthy-looking plants, which is likely to further reduce protocol adherence by smallholders. For all diseases, affected fields must be consistently

monitored for new symptomatic plants, which should then be rogued accordingly.

Chemical control using the injection of herbicides (e.g., 2,4-D and glyphosate) is an alternative roguing approach for XW and BBTD (Blomme et al., 2008; Kumar et al., 2015). However, this method is not generally recommended in ECA smallholder banana systems. Reduced adoption stems from perceived high cost, limited accessibility, prolonged period of treated plants remaining in the field, and negative effects on browsing cattle and small ruminants (Blomme et al., 2008, 2014; Kumar et al., 2015). Herbicides are no longer recommended for killing FW-affected plants. This practice is likely to encourage rapid fungal colonization of the dying plant material and induce sporulation, thereby increasing *Foc* inoculum levels (Pegg et al., 2019).

Plant debris disposal

Plant debris disposal must be tailored to prevent further spread of the pathogen or pest. For XW, bacterial ooze exuding from cut plant parts can be vectored by insects to healthy plants. However, *Xvm* bacteria do not survive long (< 35 days) in decaying plant debris (Mwebaze et al., 2006). Removed stems should be kept as intact as possible, minimizing cuts. They should be heaped at the field edge to decompose (Blomme et al., 2014).

Preventing winged aphid dispersal after plant eradication is critical for BBTV-infected debris. Above-ground stems and leaves should be chopped and quickly buried into a pre-dug hole. The debris must be covered with a thin layer of soil to prevent aphid dispersal. Subsequently, all corms should be uprooted, cut into small pieces, and left to dry on the soil in a sunny location (Personal communication, Guy Blomme, Walter Ocimati, Geoffrey Ogwal). Aphids do not inhabit corms. Leaving cut corm pieces in the sun to dry prevents resprouting.

Disposing of *Foc*-infected plant debris is particularly challenging. The pathogen can colonize and grow saprophytically in decaying material. This process increases chlamydospore production. These resistant spores allow the pathogen to persist in the soil for extended periods (Dita et al., 2018). Official protocols from Plant Protection Organizations include rigorous burning combined with the fungicide Carbendazim (Personal communication, Raman Thangavelu and Augustin Molina). Alternatively, urea may be used to accelerate decomposition (Lindsay, 2019). These practices are likely impractical in smallholder settings in ECA. As a more feasible alternative, smallholder farmers might opt for the deep burial of all infected mat debris. This eliminates a large portion of the inoculum (Personal communication, Guy Blomme).

Crop residue may also provide shelter for pests. For example, destroying crop residue is recommended to eliminate *C. sordidus* refuges and breeding sites (Masanza et al., 2005, 2006). Plant residue containing weevil larvae, specifically corms and lower pseudostems, should be chopped into smaller pieces. Leaving these pieces to dry on the soil in a sunny location accelerates tissue desiccation.

Fallowing

A fallow period is recommended after the removal of complete diseased mats. *Xvm* does not survive long in the soil without a host

(Sivirihauma et al., 2013b), and does not require a long fallow period. In intensive production systems, fallow periods of 6 and 12 months have been recommended (Turyagyenda et al., 2008; Sivirihauma et al., 2013a; Rutikanga et al., 2016). Alternatively, fields may benefit from a crop rotation cycle (Sivirihauma et al., 2013a; see Crop diversification). This short fallow period allows for the elimination of remaining corm pieces and resprouts. A 3-month fallow period is also recommended after removing BBTD-affected mats (Omondi et al., 2020), although limited data exist on pathogen survival times.

Foc spore persistence presents a major problem that cannot be overcome by standard fallowing (Dita et al., 2018). However, crop rotation and diversification can reduce inoculum levels and foster suppressive soils (see further). Flood fallowing has been implemented in FW-affected fields. This method substantially reduces pathogen survival in submerged, saturated soil after several months (Pegg et al., 2019). Nevertheless, the risk of spreading the pathogen to new areas via runoff remains substantial.

Fallowing is also an important pest control strategy, primarily to reduce populations of the banana weevil and plant-parasitic nematodes. Maintaining an absence of banana hosts for at least several weeks reduces the survival and reproduction of these pests (Risède et al., 2010; Okolle et al., 2020; Dassou et al., 2024a). Effective destruction of old banana plants is critical to prevent pest breeding (Chabrier and Quénehervé, 2003). Flood fallowing has also been recommended for managing nematodes (Tilya and Jubilant, 2012). While fallowing effectively targets weevils and nematodes due to their reliance on banana tissues, its direct effect on rust thrips is less documented. Crop rotation with non-host crops can produce effects similar to weed fallow (see Weed management).

Several weed species can serve as alternative hosts for pathogens and pests. Therefore, their presence must be controlled, even during fallow periods (see Weed management).

Clean planting material

Clean planting material is a cornerstone of disease and pest management, including tissue culture-derived plantlets, macro-propagated plantlets, and corms or suckers sourced from healthy fields. However, the banana seed system in African smallholder settings is highly informal and unregulated. It relies predominantly on the informal use and exchange of vegetatively propagated planting materials (Jacobsen et al., 2019; Mulugo et al., 2024). In affected areas, smallholders have limited access to verified disease-free sources.

In XW-affected fields, symptomless suckers can still be used as planting material at low risk (Sivirihauma et al., 2017), although those from disease-free mats are preferable. This feasibility is due to the incomplete systemic spread of *Xvm* within the mat (Ocimati et al., 2015). However, transplanted visibly healthy suckers can carry latent infections. Consequently, they require close monitoring (Sivirihauma et al., 2017). Symptomless suckers from affected areas should not be transported to disease-free areas, to prevent new incursions (Blomme et al., 2023).

In areas affected by BBTD or FW, sourcing from symptomless fields (Omondi et al., 2020) is recommended when certified or local

nursery options are unavailable. Similarly, in thrips-affected areas, suckers should be sourced from thrips-free fields and mother plants (Hara et al., 2002). Treating corms and suckers before planting is effective against nematodes and weevils. This prevents the transmission of these pests between farmers and to new fields. All roots and outer corm tissues, especially necrotic corm tissues, should be pared from the suckers. Corms should subsequently be submerged in boiling water for at least 20–30 seconds. This treatment eliminates any remaining weevil larvae and nematodes (Gold et al., 2003; Coyne et al., 2010; Hauser and Messiga, 2010).

Cultivar selection: resistant and tolerant varieties

Selecting germplasms that are moderately to highly resistant to a specific disease or pest is an effective management approach. This strategy is viable only if resistant varieties are available. For FW, using resistant or tolerant varieties in affected areas is the primary IDM component. Soil-borne spores will reinfect new banana plants for many years, if not decades (Dita et al., 2018; Munhoz et al., 2024). Various sources of resistance are available against *Foc* R1, R2 and TR4 (reviewed in Rocha et al., 2021; Thangavelu et al., 2025). Depending on their traits, these varieties can be useful in a smallholder setting. However, no commercially available alternative to the Cavendish cultivar with high TR4 resistance currently exists (Munhoz et al., 2024).

Current nematode-resistant banana germplasm offers partial, species-specific resistance (reviewed in Daneel and Mbatyoti, 2024), primarily against *R. similis*. However, no hybrid provides complete resistance against the common multi-species nematode complexes (De Waele and Elsen, 2002; Lorenzen et al., 2010). Well-established sources of nematode resistance include the wild diploid ‘Pisang Jari Buaya’ (AA), the triploid ‘Yangambi Km5’ (AAA), and new hybrids, such as ‘FHIA-01’ (AAAB) (Daneel and Mbatyoti, 2024). Despite these options, most available materials remain moderate hosts to other key nematode pests, such as *Pratylenchus* species (Coyne, 2009).

Several *Musa* germplasm accessions exhibit high resistance against banana weevils (reviewed by Okolle et al., 2020 and Bakaze et al., 2022). However, major cooking and plantain types remain highly susceptible (Kiggundu et al., 2003; Uwimana et al., 2021). Key resistant cultivars include the triploid dessert banana ‘Yangambi Km5’ (AAA) and the wild diploid ‘Calcutta-4’ (AA) (Fogain and Price, 1994; Kiggundu et al., 2003).

Currently, cultivar selection based on resistance or tolerance is not a component of management strategies for XW, BBTD or thrips. While several genotypes show a reduced rate of BBTV-infection (Kumar et al., 2015), durable resistance has not been identified or developed. Similarly, susceptibility to *Xvm* varies among genotypes (Ssekiwoko et al., 2006; Kebede and Gemmeda, 2017; Nakato et al., 2019). Nevertheless, all cultivated bananas grown in affected regions of Africa are susceptible (Blomme et al., 2023). Certain cultivars may exhibit reduced susceptibility to initial infection due to their inflorescence morphology (Mudonyi et al., 2019). In these cases, vulnerable infection sites for insects-mediated transmission are absent or undeveloped (Tripathi and Tripathi, 2009; Mudonyi et al., 2019). However, these ‘insect-escaping cultivars’ remain vulnerable to *Xvm* infection via other pathways, such

as contaminated garden tools. No documented resistance or tolerance to banana thrips is currently available.

Preventing contact with insect vectors and pests

Management of thrips focuses on preventing contact with the inflorescence. Fine-mesh polyethylene bags are used to cover the developing bunch. Application occurs just as the flower bell emerges and before bracts open (Carval et al., 2014; Ileri, 2015; Arias de López et al., 2020). Bags may be impregnated with insecticides. However, this is not compliant with organic production requirements. Other organic alternatives (e.g. Ileri, 2015; Arnaldo et al., 2021) can be used but are not critical (Arias de López et al., 2020). Spray application of insecticides for thrips control is not recommended. Sprays may achieve an immediate decline in the thrips population, but the development of resistance by these insects precludes long-term use (Fu et al., 2016, 2019). Additionally, sprays have adverse impacts on other organisms and the environment (McGuire and Northfield, 2021). Insecticide injection can present a promising alternative (Byrne et al., 2012), but research on targeted use for specific thrip species is yet to be refined. As such, thrips prevention should focus on timely bagging the inflorescence. This is likely the most effective IPM practice for small-scale farmer settings in ECA.

Trapping adult banana weevils serves as a core physical control method, leveraging the pest’s low fecundity to reduce populations before they damage the corm (Gold et al., 2003). Traditionally, farmers use split banana pseudostem traps made from crop residues, but these are labor-intensive and have variable effectiveness (Gold et al., 2002; Okolle et al., 2020). Pheromone traps provide an effective alternative (Reddy et al., 2009). However, their availability and adoption in rural and small-holder systems is limited (Walter Ocimati, 2025, Personal communication).

Preventing contact with insect vectors is crucial for managing XW and BBTD. Removing the male bud just after the formation of the last hand of the bunch is a highly effective preventive technique for XW (Blomme et al., 2017a). This practice prevents formation of the primary infection site for insect vectors (male bract and flower wounds), thereby preventing *Xvm* transmission. Bagging of the inflorescence can also prevent contact with insect vectors, birds and bats (Ocimati et al., 2013a; Nakato et al., 2014). However, this is not widely promoted, as early bud removal is faster, effective and less costly. Controlling aphid vectors (BBTV) is less straightforward because their presence is not localized to a specific plant part. While some cultural practices, such as removing old leaves, can help suppress aphid populations and minimize winged individuals, they are generally not core components of BBTD’s main IPDM strategy (Kumar et al., 2015). Quick burial of BBTD-infected mat debris (see Plant debris disposal) contributes to field-level inoculum reduction, prevents viruliferous winged aphid dispersal, and ultimately reduces new infections.

Biosecurity with focus on phytosanitary actions

Human-induced transmission is a significant factor in the spread of XW, BBTD and FW. The primary causes include the

exchange of infected planting materials (XW, BBTD, FW; see above), the use of contaminated tools (XW and FW), and the dispersal of contaminated soil (FW).

A key practice for managing XW is the regular sterilization of gardening tools. Simple household items, such as soap, detergent, bleach, or fire, can be used to disinfect tools during field work (Ocimati et al., 2021a; Blomme et al., 2023). Disinfection efforts against *Foc* inoculum and spores are particularly challenging, especially when preventing the spread of *Foc*-contaminated soil. The efficacy of *Foc* disinfection is reduced in soil suspensions and requires substantial exposure time (Nguyen et al., 2019; Salacinas et al., 2022). To prevent the spread of *Foc*-contaminated soil, efforts should focus on minimizing foot traffic and labor in the field. Additionally, soil must be thoroughly removed and disinfected from footwear, tools, farm machinery and vehicles (Dita et al., 2018; Munhoz et al., 2024). Physical fences will deter movement by both people and free-ranging domestic animals (Dita et al., 2018). Digging 50–80 cm deep ditches around sanitized banana plots can help prevent run-off (Risède et al., 2010; Dita et al., 2018).

Chemical control

Chemical controls like insecticides (e.g., Imidacloprid, Chlorpyrifos, and Oxamyl) and nematicides (e.g., Oxamyl, Fenamiphos and Ethoprophos) are available against weevils, nematodes and thrips. However, their use is often restricted to severe infestations in plantation settings due to environmental and health concerns. In addition, the availability and cost of these products often pose barriers for small-holder farmers in ECA. Fungicides have been reported to be effective against *Foc* under *in vitro* and greenhouse conditions (Nel et al., 2007; Solpot and Cumagun, 2019; Cannon et al., 2022). Evaluation under field conditions is recommended.

Part 2. Supporting field management practices strengthening IPDM

Crop diversification

Crop diversification can play a key role in an IPDM strategy. It modifies aboveground vegetation structure, thereby altering habitats, forming physical barriers to dispersal, and changing the microclimate. These changes impact pests, insect vectors and their natural enemies (e.g., predators and parasitoids) (Boudreau, 2013; Blomme et al., 2023). Additionally, diversification can positively alter the soil microbiome, contributing to disease suppression (Du et al., 2024; Xu et al., 2024). Various approaches exist for diversifying cropping systems. These include cultivating a mixture of banana cultivars or varieties, intercropping with food, cash, or fodder crops, and introducing canopy and cropping layers for shade via agroforestry systems. Other methods involve utilizing cover crops to protect bare soil and implementing crop rotation to diversify cropping over time. When the goal is to enhance the soil microbiome, crop diversification can be effectively combined with

biocontrol methods and the application of organic soil amendments (Du et al., 2024) (as discussed further). However, diversifying the cropping system requires careful planning. Some weeds or introduced plants could inadvertently exacerbate or perpetuate specific crop pests and diseases, particularly if they act as alternative host plants.

Improved soil microbiomes, fostered by plant diversification, can confer protection against pathogens. This protection occurs through direct pathogen inhibition, resource competition, and the activation of plant immune responses (Du et al., 2024). Studies on crop rotation and intercropping with *Allium* plants, such as Chinese chive, have frequently demonstrated suppression of FW in various crops (Nishioka et al., 2019, 2022; Yan et al., 2023), including banana (Huang et al., 2012; Zhang et al., 2013; Li et al., 2020; Torres-Bedoya et al., 2025). Researchers attribute the positive impact of *Allium* plants to allelopathy, stemming from the release of bioactive compounds, as well as beneficial shifts in microbiome diversity and soil structure. Specifically, *Foc* spore germination and hyphal growth can be inhibited by antifungal molecules and volatiles released by *Allium* plant roots. Alternatively, these effects may result from alterations in the soil microbiome. Beyond *Allium* plants, crop rotations with pineapple, pepper, or eggplant have also shown promise in suppressing FW (reviewed in Munhoz et al., 2024). For instance, chili pepper-banana rotation alters soil physiochemical properties, thereby optimizing niches for beneficial soil microbiomes (Hong et al., 2020). Pepper-banana and eggplant-banana rotations has been found to enrich nine antagonistic core microbial taxa (Hong et al., 2023). In contrast, pineapple-banana rotation is associated with an increase in soil fungi that exhibit *Foc*-inhibiting effects (Yuan et al., 2021; Yang et al., 2023). Critically, the effectiveness of pathogen suppression through diversification is highly dependent on the specific combination of crop species. Several crops, such as maize (Wang et al., 2015) or beans (Karangwa et al., 2016; Ren et al., 2024), show minimal or no impact, while others have yet to be investigated. Overall, the precise mechanisms underlying *Foc* suppression remain only partially understood (Nishioka et al., 2019). Furthermore, translating promising laboratory or pot trial findings to effective field applications has proven challenging. This difficulty complicates targeted interventions (Russ et al., 2023). While crop rotation can foster the development of soils suppressive to FW, whose spores can persist in the soil for many years, it also serves as a simple break crop for other pathogens (Blomme et al., 2014). For instance, *Xvm* bacteria do not survive long in the soil without a host (Sivirihauma et al., 2013b). Therefore, a short rotation period can be sufficient for its control through inoculum elimination (Rutikanga et al., 2016).

Using cover crops in banana production represents a sound agricultural practice. These cover crops help manage water and soil erosion, and control weeds. Similar to intercropping and crop rotation, they also positively influence the soil's physical, chemical, and microbiological properties. With careful selection, specifically by avoiding alternative hosts, cover crops can also support pest and disease management (Dita et al., 2018; Xu et al., 2024).

Diversification through the cultivation of a mixture of banana cultivars can also enhance overall crop tolerance to FW, especially when combining susceptible, tolerant, and resistant varieties. It has

been hypothesized that variations in the biochemical root composition and root exudation of diverse cultivars could modulate changes in the soil microbial community. Alternatively, these variations may directly contribute to increased resistance of co-cultivated, more susceptible banana cultivars (Wuyts et al., 2007; Deltour et al., 2017). However, these findings rely largely on field observations showing that mixed cultivar cropping reduces overall *Foc*-susceptibility. Research into the underlying mechanisms of suppression remains limited. Similar reductions in the severity of XW infections have been observed in farms utilizing a mixture of banana cultivars (Uwamahoro et al., 2019). These reductions are potentially related to variations in insect behavior and cultivars preference. Blomme et al. (2017b, 2023) further suggested that an increased presence of “escape cultivars” (see section on host resistance) can reduce the risk of XW establishment and spread. Moreover, diversified banana production systems incorporating plantain and banana are associated with reduced BBTD prevalence and risk (Dato et al., 2021). Differences in banana aphid preference may explain the decreased BBTD incidence in mixed stands, although causal links have not been assessed. Dato et al. (2021) observed a significant association between intercropping and reduced BBTD. They linked this reduction to decreased aphid habitat suitability, reduced banana canopy connectivity, and limited mat-to-mat dispersal by aphids. Trap plants, which attract and divert aphids away from host plants, have been proposed for aphid management, but their effectiveness against banana aphids has not yet been tested (Ben-Issa et al., 2017). Field isolation and physical border vegetation (hedges) of different species was also associated with reduced BBTD incidence (Niyongere et al., 2013; Dato et al., 2021).

Crop diversification in all its forms (intercropping, rotation, cover cropping, banana varietal mixtures) also presents a key strategy for pest management, with varying success across taxa. Prolonged banana monoculture exacerbates pest pressure and shifts the soil food web toward parasitic species. In contrast, intercropping systems often introduce associational resistance, effectively suppressing nematode populations (Zhong et al., 2012; Chadfield et al., 2022). This control mechanism depends heavily on the choice of the intercrop species, which often acts as an antagonist or trap crop (Viaene et al., 2024). For instance, species such as marigold release nematicidal root exudates. Root crops such as sweet potato have also demonstrated significant efficacy when used in combination with arbuscular mycorrhizal fungi (Mandou et al., 2023). Conversely, the impact of intercropping on the banana weevil is frequently neutral or inconsistent. This is because its damaging larval stage is concealed within the corm, which is largely unaffected by surface-level crop changes. Studies evaluating common legume intercrops, such as groundnut and *Mucuna*, show no significant reduction in weevil populations or corm damage (McIntyre et al., 2001; Rukazambuga et al., 2002). These findings suggesting that intercropping is not a suitable control option for weevils. Duyck et al. (2011) also observed that the addition of *Brachiaria decumbens* intercrop did not change the trophic niche of *C. sordidus*, but that it did change the trophic position of its generalist predators. Duyck et al. (2011) concluded that the cover crop provided resources that likely supported a community of insect

herbivores. These herbivores acted as alternative prey for generalist predators, resulting in a neutral effect of predation. In contrast, Mollet et al. (2012) observed that adding a new primary resource in the form of cover crops increased the abundance of the ant *Solenopsis geminata* Forel (Myrmicinae). This led to increased predation of weevil eggs by 1.3- to 6.3-fold. The impact of cover crops on weevils could thus vary with cover crop species.

Many species of thrips, including those infesting bananas, are polyphagous. They feed on a wide variety of plants. However, limited information is available on the impact of crop diversification on banana thrips. For example, recent field observations suggest a reduced abundance of banana rust thrips in more diverse banana cropping systems (Dassou et al., 2024b). This aligns with the understanding that diversifying crops can modify habitat and environmental conditions. Consequently, these modifications make habitats either more or less favorable for particular thrips species (Rodríguez and Coy-Barrera, 2023). Furthermore, crop diversification can foster the presence and activity of natural enemies, such as predatory insects or mites. These organisms help control thrips populations. Another strategy involves introducing trap crops. These are sacrificial plants highly attractive to thrips that divert them away from the main banana crop (Ileri, 2015). Despite these potential benefits, comprehensive studies remain scarce. Few investigating specifically address the effects of crop diversification strategies on banana thrips.

All positive impacts of intercropping, crop rotation or cover cropping can be undone by inadequate crop selection, specifically by using alternative hosts. Several crops can serve as alternative hosts. For instance, *Canna indica*, millet and sorghum are potential hosts for *Xvm* (Ocimati et al., 2018). Ginger, turmeric, *Canna indica* and taro can host BBTV (Pinili et al., 2013; Rahayuniati et al., 2021). Banana aphids can also act as vector to and from alternative hosts, feeding sufficiently to transmit BBTV (Watanabe et al., 2013). Enset and *Canna indica* crops, along with several ornamental plants, weeds and grasses can also serve as host for *Foc* (Olivares et al., 2021). Sweet potato and sorghum are intermediate hosts for *R. similis*. Additionally, sorghum-sudangrass has been reported as a good host (Van der Veken et al., 2008).

Increased management needs for intercropping can also undo their overall positive impact on disease management. For example, banana leaf pruning to reduce shade for the intercrop, a common practice on smallholder farms, can increase XW transmission via contaminated tools (Blomme et al., 2023). Indeed, increased XW incidence in intercropped fields has been observed during field observations (Uwamahoro et al., 2019). Increased field visits can also increase pathogen dispersal in FW-affected fields. Workers can transfer *Foc*-spore-bearing soil adhering to shoes, clothes and farm tools. Cover cropping in FW-affected fields with a non-host crop could be a good alternative, as it would require less management and field visits. Reduced soil erosion and reduced contact of footwear with soil particles will further decrease the spread of spore-bearing soil.

Weed management

Various weed species can serve as alternative hosts for specific pests, insect vectors and diseases, thereby maintaining inoculum in

the field (Hennessy et al., 2005; Ocimati et al., 2018; Olivares et al., 2021; Catambacan and Cumagun, 2022; Parac et al., 2024; Carval et al., 2014; Suparman et al., 2017). As such, weed management should be an integral component of the IPDM strategy.

Nonetheless, the act of weeding itself requires careful consideration to avoid exacerbating disease spread. For instance, Ocimati et al. (2018) identified the weed *Canna* spp. as an alternative host for *Xvm*. However, on-farm observations indicated that the presence of *Canna* spp. did not directly influence XW incidence. The researchers attributed this discrepancy to the weed's limited infection potential. Nevertheless, they also highlighted an increased risk of disease dispersal through tool transmission during weeding. Similarly, in fields infected with *Foc*, weeding can inadvertently spread spore-bearing soil. Disturbing *Foc*-infected weeds may also increase spore production, thereby elevating inoculum levels. Moreover, similar to intercrops or cover crops, weeds can alter the soil microbiome and influence the soil's suppressive nature. Catambacan and Cumagun (2021) identified antagonistic activity of fungal endophytes against *Foc* TR4 isolated from weeds growing in Cavendish banana farms. This suggests a complex interaction where complete weed eradication may not be optimal if those weeds host beneficial microbes.

Weeding serves as an effective cultural control measure against pests. For parasitic nematodes, weeding is vital. Many common weed species act as alternate hosts or reservoirs, allowing nematodes to reproduce and maintain high populations that continuously reinfest banana roots (Quénéhervé et al., 2006). Weeds can also support a diversity of thrips species in and around banana farms (Sánchez-Monge et al., 2011; Njue et al., 2025). Weeding influences overall habitat suitability for banana thrips and host plant availability, thereby reducing thrips numbers. While direct removal of host weeds is generally beneficial, some studies suggest complex interactions. For example, Carval et al. (2014) found that the abundance of banana rind thrips (*E. brevisetis*) on banana crops was negatively correlated with the presence of specific weeds. This suggests these weeds attract rind thrips and could be utilized for *E. brevisetis* management. Similarly, Hauxwell (2008) noted that thrips can migrate from weed vegetation to irrigated crops when weed hosts dry out, highlighting the role of weeds as reservoirs. Since plant-thrips associations are species-specific, refining weeding practices by understanding the preferred habitats of local thrips pest species is crucial (Sánchez-Monge et al., 2011; Ileri, 2015).

Weeding significantly impacts BBTd management beyond removing alternative hosts for BBTv (Parac et al., 2024). It affects the primary vector, the banana aphid, both directly and indirectly. Dense weed growth around banana mats creates sheltered, humid microclimates where aphids thrive (Hooks et al., 2011). Weeding eliminates these protective environments. This exposes aphids to unfavorable conditions, such as direct sunlight and wind, as well as predators. Furthermore, certain weed species serve as alternative hosts for banana aphids (Suparman et al., 2017). These hosts allow aphids to persist and build up populations even when banana plants are scarce. Removing these alternative hosts disrupts the aphid life cycle and diminishes overall vector pressure. However, weed removal can also reduce the diversity and population size of natural enemies.

Banana planting density

Banana planting density can significantly influence disease epidemiology, severity, and pest habitat suitability. Direct studies on the effect of density on specific banana diseases are limited. However, field observations generally show fewer infections with wider spacing for FW and XW (see Supplementary Information Supplementary Table 1). This improvement likely results from reduced canopy and root connectivity, which limits pathogen exchange. Better air circulation and lower humidity also contribute. However, the impact of spacing may be minimal in the case of XW. For instance, spacing offers little benefit if farmers use contaminated garden tools across their fields, or fail to practice early de-budding to prevent insect-vectored transmission.

BBTD is also likely to worsen with higher planting densities. This occurs primarily because dense canopies create more favorable aphid habitats. These habitats are characterized by higher humidity and reduced airflow, which facilitate population build-up and the development of winged individuals. Regarding banana pests specifically, limited studies are available on the impact of banana planting density. However, research on other thrips species shows varied responses. For instance, some species, such as cotton thrips, are more abundant at lower densities (Krob et al., 2022), while others, like Western Flower Thrips, thrive in higher densities (Rodríguez and Coy-Barrera, 2023). Since banana thrips rarely fly, higher banana planting densities with overlapping leaf canopies may favor mat-to-mat movements. Denser banana plantations with overlapping root systems will also favor natural nematode spread from mat to mat. Additionally, these conditions increase overall carrying capacity (Tixier et al., 2006; Seenivasan, 2017). Higher planting densities may also shorten the time required for pests to locate suitable host plants. This can lead to increased infestation pressure and greater damage.

Removal of excess suckers and leaves

De-trashing (pruning old and wilted leaves) offers general field management benefits for banana mats. However, this practice is not recommended in XW-affected areas. In these regions, pruning and de-suckering must be suspended to prevent disease spread via contaminated farming tools (Addis et al., 2008; Kubiriba et al., 2014). Although proper sterilization of tools can eliminate *Xvm* inoculum from blades (Ocimati et al., 2021a), surveys indicate that farmers often perceive this process as time-consuming and costly (Blomme et al., 2019). Consequently, farmers may become less vigilant and inconsistent with tool sterilization protocols. Therefore, suspending de-trashing and de-suckering operations until no affected plants have been observed for at least 3 months is a more realistic and effective strategy. Where necessary, such as to reduce shade for intercrops, excess leaves can be bent at the petiole level by hand or with a hooked wooden stick (Blomme et al., 2017a; Kikulwe et al., 2022).

Similar concerns regarding increased spread risk due to increased field management also apply for FW. *Foc* can spread via spore-infested soil adhering to farm tools, footwear, or clothing of workers in the field (Ploetz, 2015). Additionally, Warman and

Aitken (2018) identified chlamydospore production in and on outer leaf sheaths of *Foc*-infected banana plants, even before symptom onset. Therefore, deleafing and using detached leaves as mulch can increase soil inoculum levels. Garden tools used on *Foc*-infected mats can facilitate disease spread if not sterilized (Dita et al., 2018; Nguyen et al., 2019).

Deleafing and desuckering can reduce BBTD spread via aphids by reducing favorable aphid habitats and preventing large aphid colony build-up. Niyongere et al. (2013) identified that suspending pruning during dry seasons, a common practice as pruning is typically done in the rainy season to provide light for intercrops, leads to dense, bushy banana mats. These dense mats create ideal breeding grounds for aphids. This increases the risk of winged aphid formation and BBTD transmission.

The precise impact of deleafing or desuckering on banana thrips remains unclear, partly due to variations in species-specific life cycles. For instance, Carval et al. (2014) demonstrated that suckers play a crucial role in the movement of banana rind thrips from the soil to the mother plant and subsequently to the banana bunch. This suggests that desuckering could effectively reduce rind thrips infestations. IPM recommendations for thrips often advocate removing selected leaves and flower remnants to reduce habitats or eliminate thrips sources (Hara et al., 2002; Cabrera et al., 2010; Wang et al., 2016a). However, these recommendations are often made without a full understanding of the life cycle of the thrips species at hand.

Tillage

To our knowledge, no specific research addresses the direct impact of tillage on XW or BBTD. However, tillage operations may cut superficial roots of XW-infected mats. This action could enable the transfer of *Xvm* bacteria from contaminated tool onto root systems of healthy mats (Ocimati et al., 2013b). Superficial tillage is thus advised in XW-affected fields.

Tillage may increase the spread and severity of FW in banana plantations. Tillage operations may physically move *Foc* spores (e.g., with soil particles adhered to weed roots) from infected to healthy parts of a field. This process would contribute directly to the pathogen's dispersal (Dita et al., 2018). Furthermore, the mechanical damage caused by tillage creates new entry points for the pathogen on banana roots, increasing susceptibility to infection.

Tillage is expected to impact banana thrips, particularly species like the banana rust thrips (*Chaetanaphothrips signipennis*) which have a pupal stage in the soil. However, no specific studies are available on this topic. Conservation tillage, in contrast to conventional tillage, has been shown to reduce thrips numbers for specific species (cotton thrips, Manley et al., 2002; Toews et al., 2010; Knight et al., 2017), although not always (cotton thrips, Gencsoylu and Yalcin, 2004). Additionally, conservation tillage, as part of agroecological production systems, has been shown to improve regulation of plant parasitic nematodes (Loranger-Merciris et al., 2023).

Mineral fertilization

Inorganic fertilizers are routinely applied to bananas to increase production. However, depending on the mineral used, they may induce suppression or exacerbation of plant diseases (Olivares et al., 2021). High levels of nitrogen, particularly in the ammonium (NH_4^+) form, are frequently linked to increased incidence and severity of FW (Zhou et al., 2017; Orr and Nelson, 2018). Conversely, nitrate (NO_3^-) fertilizer has been shown to provide protection to plants from FW (Wang et al., 2016b; Mur et al., 2017; Zhou et al., 2017). However, Orr et al. (2022) found that increased application of both nitrate and ammonium was significantly positively correlated with disease severity in banana. This relationship between N form and disease progression may be due to the acidifying effect of ammonium fertilizer. Soil acidification improves *Foc* survival and increases FW severity (Teixeira et al., 2021; Segura et al., 2022). Nevertheless, each soil differs in its response due to varying soil properties. This variability complicates the development of standard soil management strategies, such as N-fertilization and liming, to mitigate banana FW (Bowen et al., 2019). He et al. (2023) suggested that treating banana crops with a combination of organic and inorganic (i.e., nitrate) nitrogen could be a better alternative for managing FW.

Fewer trials are available on the impact of fertilization with other minerals or mineral combinations on banana FW. Nowembabazi et al. (2021) investigated the effect of integrated potassium management (including inorganic K, manure, and potassium solubilizing bacteria) on FW tolerance in apple bananas. Their screenhouse trials demonstrated significantly reduced FW symptom expression associated with integrated potassium management. In field settings, Clarke et al. (2024) observed a small increase in the abundance of *Fusarium* populations in banana roots following phosphorus addition (although not all were pathogenic *Fusarium*).

Research specifically on the impact of inorganic fertilizers on XW under field conditions is not available (to our knowledge). Under laboratory conditions, Atim et al. (2013) suggested that applying potassium, nitrogen, and calcium could be part of an integrated approach to reduce XW incidence and prolong the incubation period. This indicates that specific nutrient levels might enhance a plant's inherent resistance. However, pot experiments by Ochola et al. (2014) presented a contrasting view. Their findings showed that increasing NPK fertilizer amounts did not significantly reduce disease incidence, severity, or plant mortality in artificially inoculated banana plantlets. This suggests that, at least in their experimental setup, higher fertilizer application didn't offer a strong protective effect against the disease. Mburu et al. (2016) further identified that silicon (Si) application enhanced resistance to XW in pot experiments, resulting in delayed onset symptoms. Field observations conducted between 2003 and 2025 in the ECA region, across XW-affected landscapes with varying soil types and fertility levels, have not revealed any consistent patterns in XW incidence or field-level prevalence. These observations indicate that soil type or

fertility level might not be a major determinant of disease expression (Guy Blomme, Pers. Comm.).

To our knowledge, few studies have examined the impact of inorganic fertilizers on BBTB, banana aphids, or banana pests. Reduced BBTB incidence after NPK application has been reported in a single experiment, but was not replicable at a second site (Kayira, 2023). It is plausible that fertilizer-enhanced banana plant growth could indirectly support larger aphid populations (Kayira, 2023). This could lead to an increase in winged aphids mediating the spread of the virus. However, no further research is available to confirm this link. Similarly, the impact of inorganic fertilizers on banana pests is likely indirect. These effects influence the host plant's physiology, nutritional quality, and growth. For example, modifying fertilization practices has been effective in reducing the populations of other thrips species (western flower thrips on roses: Chow et al., 2012; sugarcane thrips: Keeping et al., 2014; Thrips palmi on cucumbers: Ren et al., 2022). However, this strategy has not yet been studied for banana thrips.

Organic amendments

Organic soil amendments, such as compost, crop residues, farmyard manure, neem cake, and off-field sources, can promote soil structure, nutrient availability, microbial activity, and overall soil health (Creamer et al., 2022). Consequently, they can play a critical role in inducing soil suppressiveness (Sagova-Mareckova et al., 2023). Few field trials assessing the impact of organic amendments on FW report a reduction in disease incidence (see Supplementary Information [Supplementary Table 1](#); Bonanomi et al., 2007; Olivares et al., 2021). This outcome is primarily achieved by improving soil health through promoting a more diverse and active microbial community in the rhizosphere. The introduction of beneficial microorganisms, often present in composts or supplemented in bio-organic fertilizers (see further, Biocontrol), can lead to direct antagonism against *Foc*. These mechanisms include competition for nutrients and space, or by producing antifungal compounds (Solórzano et al., 2025). Additionally, organic matter can enhance the plant's natural defense mechanisms and improve its ability to resist infection (Bonanomi et al., 2018).

Organic amendments can also be part of an effective strategy for managing parasitic nematodes in banana crops. Regulation of *R. similis* has been observed in agroecological systems characterized by low agrochemical use (Loranger-Merciris et al., 2023). This finding is consistent with pot trials (Pattison et al., 2006, 2011; Tabarant et al., 2011) and limited field trials (Pattison et al., 2006). In field trials, placing crop residue and high-carbon amendments around the base of the banana plant, combined with a reduction in the nitrogen applications, was associated with the suppression of PPN. However, this effect exhibited lag times of up to two years (Pattison et al., 2006). This suppressive effect is linked to improvements in soil health, specifically an increase in the diversity and functional composition of the beneficial non-parasitic soil nematode community. However, a range of mechanisms could be involved (Oka, 2010).

It is important to note that the effectiveness of organic amendments can be influenced by various factors, including the type, composition, and quality of the organic material, soil properties, as well as the specific pathogen and host plant combination (Bonanomi et al., 2010, 2018; Tiltonell and Giller, 2013). Ensuring the quality of organic amendments in smallholder settings presents significant challenges that can undermine their effectiveness in disease control (Tiltonell and Giller, 2013).

No specific literature on the impact of organic amendments on banana XW or BBTB was found. A positive impact might be expected because of enhanced soil microbial communities and disease suppression, similar to the impact of crop diversification. Although, as neither *Xvm* or BBTB are soil-borne pathogens, the impact could be very minimal. Overall improved plant performance and natural defense through enhanced soil fertility and health could also be expected.

Similarly, to our knowledge, no studies are available on the impact of organic amendments on banana thrips or weevils. As noted previously, improved soil health may enhance the banana plant's resistance to pest pressure. Additionally, organic amendments can directly interfere with thrips life cycle. This is particularly relevant for species like the banana rust thrips, which have a pupal stage in the soil or leaf litter (Hara et al., 2002). Conversely, organic amendments could create a suitable environment for banana weevil propagation (see Mulching).

Biocontrol

A lot of research effort has gone into identifying biological control agents against *Foc* as a sustainable and effective control strategy [reviewed by Bubici et al. (2019) and Solórzano et al. (2025), among others]. A diverse selection of microbial agents has been identified with high efficacy for controlling *Foc*. These agents operate through various modes of action and often provide additional benefits for plant development (Solórzano et al., 2025). In these studies, trials are generally initiated *in vitro* (under strictly controlled laboratory conditions). Subsequently, they progress to greenhouse and experimental plot trials to more closely resemble field conditions. Under field conditions, while notable results have been achieved (Supplementary Information [Supplementary Table 1](#)), their efficacy remains inconsistent. Results depend heavily on the local environment, microbial composition of the rhizosphere and roots, crop growth status, and the formulation and application method of the biocontrol agent(s), among other factors. This complicates the development of standardized protocols.

Furthermore, a critical scaling challenge lies in the complexity of producing large volumes of a biocontrol mixture and ensuring regular quality control at the small- to mid-scale farm level (personal communication, Guy Blomme). Since these mixtures ideally require repeated applications over extended periods, their feasibility in small-scale farming systems is limited.

Biocontrol of *Xvm* or BBTB is even further from field application. Few studies have demonstrated that treatment with antagonistic bacteria can suppress *Xvm* in controlled settings (Abayneh, 2010; Mahuku, 2016). Similarly, some studies report reduced

incidence of BBTV through induced systematic plant resistance, even in field trials (Kavino et al., 2008, 2009; Harish et al., 2009a, 2009b). These approaches remain in an exploratory phase.

Biological control presents several approaches for managing banana pests and insect-vectors. While biocontrol of banana aphids is not a common practice or recommendation, recent studies have shown several entomopathogenic fungi (e.g. genera *Aspergillus* and *Beauveria*) to induce aphid mortality and reduced fecundity (Tricahyati et al., 2022; Enoh et al., 2024). These findings, along with the potential of other natural enemies (Tricahyati et al., 2022), highlight an alternative approach to reduce the spread of BBTV. Specific entomopathogenic fungi have also been shown to induce mortality in banana thrips (Clercx et al., 2015; McGuire and Northfield, 2021). Treated banana bunches remaining marketable (McGuire and Northfield, 2021), and these fungi show potential for biopesticide development. Other natural enemies of banana thrips, including parasitic wasps and predatory mites, have been shown to reduce thrips numbers, but to a lesser extent (Arias de López et al., 2020; Cabezas-Guerrero et al., 2025). For the banana weevil, biocontrol remains challenging due to the pest's behavior and natural resistance. Classical biological control largely ineffective (Tresson et al., 2021). Generalist predators, particularly ants capable of attacking weevil eggs and larvae, are promising (Abera-Kalibata et al., 2008). However, a better understanding of the weevil's ecological network in the field is needed. For nematodes, although several biocontrol agents are available (see Viaene et al., 2024; Daneel and Mbatyoti, 2024), field application is notoriously difficult and often produces inconsistent results (Viaene et al., 2024). Ultimately, biocontrol adoption is currently limited among small-scale farmers. Moreover, the introduction of such biocontrol agents is recommended only for highly localized and infrequent applications. This is because biocontrol can reduce beneficial organisms and impact overall biodiversity within the field (Arias de López et al., 2020).

Mulching

Mulching differs from other soil organic amendments through its surface application with the purpose to cover the ground to reduce runoff, conserve moisture, suppress weeds, and regulate soil temperature. As organic mulch decomposes, it gradually adds organic matter to the soil below, providing suppressive benefits as discussed above.

From a pest management perspective, mulching generally has a negative impact on the banana weevil. This occurs despite the benefits of mulch for crop growth and yield. Several studies have shown that weevil populations tend to be higher in mulched plots than in unmulched ones (Gold et al., 2006; Coyne et al., 2006). This suggests increased weevil longevity and survival in moist soils (Rukazambuga et al., 2002; Okolle et al., 2020). Other studies found no effect of mulching (e.g. Oliveira and Souza, 2003; Tinzaara et al., 2008). Because *C. sordidus* is highly susceptible to desiccation, mulching creates a more suitable, damp microenvironment for the pest to thrive and multiply (Bakaze et al., 2022; Viaene et al., 2024). Furthermore, weevils reportedly are more active and move longer distances in mulched areas (Gold et al., 2006).

Conversely, improved plant health promoted through mulching has shown improved production capacity even under nematode pressure (Coyne et al., 2005; Rotimi et al., 2004). High applications of *Tithonia* mulch have been documented to suppress nematodes. This suppression occurs by reducing the galling indices associated with *Meloidogyne* spp. and root necrosis due to *R. similis*. Additionally, *Tithonia* mulch creates conditions that favor antagonistic soil microbes (Coyne et al., 2006). However, the trade-off involves creating more favorable conditions for banana weevils. This dynamic could tip the scales to increased nematode damage (see Control of exacerbating pests).

Reflective mulches, such as plastic or metalized UV-reflective mulches, show potential for deterring thrips. Organic mulches can indirectly contribute to weed suppression, which may reduce thrips harborage (Ngosong et al., 2019; Razzak et al., 2019; Hossain et al., 2022). Nevertheless, limited research exists on the impact of various mulching practices on banana thrips populations. It is speculated that banana thrips with a pupal stage in the soil could be affected by mulching, but no research is currently available to support this hypothesis. Further research is needed to determine the most effective mulching strategies for specific banana thrips species and regional conditions.

Organic mulches can be a valuable addition for managing FW, although specific field trials are limited. Beyond their contribution to overall soil health (e.g. Kidane and Laing, 2010), certain mulches can have a direct fungicidal impact. A pot experiment by Orr et al. (2022) showed that mulch from *Eucalyptus cloeziana* significantly reduced disease severity. This effect is likely related to bioactive compounds within the wood. On the other hand, mulching has been linked to higher densities of banana weevils (McIntyre et al., 2003), leading to greater plant damage and increased susceptibility to infection (see Control of exacerbating pests).

Again, limited information is available on the impact of mulching on XW, BBTD, or banana aphids. Research on other aphid species shows that mulching can significantly reduce aphid populations. Both reflective and organic mulches can deter aphids (Summers et al., 2005; Niemann et al., 2022; Winkler et al., 2025). Conversely, organic mulches could also provide a more favorable environment for both aphids and their natural enemies, by creating a cooler, more humid microclimate at the base of the plant. Alternatively, mulches may deter aphids and disrupt their landing (Gill et al., 2011).

Control of exacerbating pests

Banana weevils and nematodes damage the banana plant's root system and corm. This damage may facilitate *Foc* infections (Dita et al., 2018). Furthermore, both *Foc* and *Xvm* have been found in and on banana weevils (Were et al., 2015; Guillen Sanchez et al., 2021). These pests serve as potential vectors of these diseases via wounds they create in the corm tissue (Heck et al., 2021). Weevils and nematodes also exhibit a synergistic interaction, where together they cause exponentially greater damage than when acting separately (Gold et al., 2001). Management of these pests should be included in an integrated approach to control various banana diseases (Risède et al., 2010; Tixier et al., 2010; Okolle et al., 2020).

Irrigation

Irrigation practices play a critical role in the spread and severity of FW, primarily by facilitating the movement of the spores (Dita et al., 2018; Liu et al., 2019; Munhoz et al., 2024). *Foc* spores can survive for several months (> 120 days) in running water, although viability is reduced in stagnant water (Ullah et al., 2021). Therefore, management of irrigation sources and runoff is critical, and intake from contaminated areas must be prevented (Dita et al., 2018). However, this is easier said than done, as irrigation sources or overall water flow are often uncontrolled, especially in small-scale banana production systems.

The impact of irrigation on other pests or diseases is less clear. Irrigation may influence banana aphid vectors by affecting their feeding habits, lifespan, or reproduction (Van Munster, 2020). These changes could impact the spread of BBTV, although this relationship is not well-documented. To our knowledge, no research is available on the influence of irrigation on banana thrips. Irrigation methods are reported to influence other thrips populations, although this is dependent on the species (Nelson et al., 2006; Ileri, 2015; Rodríguez and Coy-Barrera, 2023).

Conclusions

Managing co-occurring biotic threats in smallholder banana cropping systems across East and Central Africa is a critical challenge. Sustained productivity requires the strategic adoption of IPDM. This approach begins with the farmer's capacity for accurate, timely diagnosis. Correctly identifying the specific complex of pathogens or pests present dictates the response efficacy. Successful IPDM demands the integration of cohering practices, like using clean planting material, which simultaneously mitigates multiple threats. Furthermore, adopting multiple, mutually supportive management practices in parallel is essential for achieving a cumulative, long-term reduction in pest and disease pressure. Conversely, protocols must strictly avoid conflicting practices. For example, implementing crop diversification strategies without considering that certain crops may serve as alternative hosts for specific banana pathogens or pests can be counterproductive. The viability of IPDM ultimately rests on its feasibility for smallholder farmers. Therefore, strategies must focus on accessible, low-cost cultural controls that balance ecological sustainability with immediate economic realities.

Author contributions

GB: Resources, Project administration, Conceptualization, Writing – review & editing, Supervision, Funding acquisition,

Writing – original draft. EK: Writing – review & editing, Writing – original draft, Methodology, Conceptualization, Visualization. WO: Methodology, Writing – review & editing.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fagro.2026.1757848/full#supplementary-material>.

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