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Review

Fusarium Wilt of Banana: Challenges and Resilience

Shanta Adhikary, Mridula Rahman, Mrinmoy Kundu, Md. Al Emran Hosen and Md. Motaher Hossain

Department of Plant Pathology, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur, Bangladesh

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Corresponding Author:
Md. Motaher Hossain
Department of Plant Pathology, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur, Bangladesh
Email: hossainmm@bsmrau.edu.bd

Abstract: Banana, as the world's most consumed fruits, are an essential staple crop for nearly 400 million people, boasting a plethora of nutrients crucial for digestive health, gut microbiome balance, and post-exercise recovery. Despite their nutritional significance, the emergence of *Fusarium* wilt, caused by *Fusarium oxysporum* f.sp. *cubense* (Foc), threatens banana cultivation worldwide. This soil-borne fungus exhibits polycyclic behavior, persisting in soil for extended periods and impacting various banana cultivars through complex disease cycles. Identification of *Fusarium* wilt involves observing external and internal symptoms, with comprehensive diagnosis essential for effective management. Sustainable strategies including crop rotation, intercropping, organic amendments, and biological control agents offer promising avenues for disease mitigation. Additionally, transgenic approaches hold the potential for developing resistant banana varieties, though commercial acceptance and long-term field data remain challenges. Climate-smart management practices adaptable to changing environmental conditions are crucial for future resilience. This study reviews the comprehensive knowledge of the geographical distribution, diagnosis, impact, disease cycle, factors affecting outbreaks, and various management strategies of FW in bananas. By highlighting the challenges posed by *Fusarium* wilt and offering innovative solutions, the manuscript contributes to building resilience within the banana industry.

Keywords: Disease Dynamics, Causal Factors, Sustainable Management, Bio-Control, Transgenic Approaches

Introduction

Bananas are presently holding the title of the world's most consumed and exported fruit. Along with plantains, they are the world's fourth most important staple crop, vital to the sustenance of food and nutrition security for almost 400 million people in producing nations (IISD, 2023). Packed with nutrients, they contribute to preventing constipation, improving digestive and gut health, and aiding recovery from intense physical activity. Moreover, banana is rich in fiber, potassium, vitamin B6, vitamin C, antioxidants, and phytonutrients (Arnarson, 2023) while consuming one banana daily, provides 12% of the Daily Value (DV) for vitamin C, 10% for potassium, and 8% for magnesium (Rose-Francis and Bjarnadottir, 2023). The culinary versatility of bananas is evident in both ripe and raw forms. Ripe banana is enjoyed as a nutritious fruit, while slightly green ones are incorporated into savory dishes. One medium-ripe banana offers approximately 110 calories, 0 g of fat, 1 g of protein, 28 g of carbohydrates, 15 g of naturally occurring sugar, 3 g of fiber, and 450 mg of potassium (The Nutrition Source, 2018). Raw banana is used in diverse dishes like raw banana curry, banana chips, and raw banana cutlets. Furthermore (Fig. 1), banana peels are repurposed in Indian households for cleaning, leather polishing, and composting, promoting circular economy principles and waste reduction (Bree, 2023). For a variety of mouthwatering banana recipes, ranging from banana bread and muffins to pancakes, brownies, carrot cake, oatmeal, French toast, smoothie bowls, and banana ice cream, readers can explore a compilation by Esile (2020). Integrating banana plants into agroforestry or mixed cropping systems enhances overall ecosystem resilience. In comparison to other shade trees, bananas, for example, reduce water competition by providing vital shade for climate-sensitive coffee crops and by maintaining hydration under drought stress (First, 2016). Global banana production has surged from 69 million tonnes in 2000-2002 to 115 million tonnes in 2017-2019, with an approximate value of 40 billion USD (FAO, 2020). However, the banana supply chain is vulnerable to global disruptions, such as those induced by the COVID-19 pandemic, the Russia-Ukraine conflict, and fluctuations in fossil fuel prices. Environmental challenges and the lack of genetic diversity expose plantations to increased risks from pests and diseases exacerbated by climate change (IISD, 2023). Fusarium Wilt (FW), caused by the fungus *Fusarium oxysporum* f.sp. *cubense* (Foc), poses a significant threat to various banana cultivars worldwide (Kema *et al*., 2021). While knowledge exists on Foc's biology and genetic diversity, critical gaps remain in understanding its biogeography, particularly regarding soil, climate, and agro-environmental factors influencing its spread (Shabani *et al*., 2014). This information is vital for effectively managing this phytosanitary challenge. Furthermore, FW-induced yield losses are substantial and the fungus exhibits resistance to synthetic chemical fungicides, necessitating eco-friendly alternatives. Sustainable management practices like resistant cultivars, organic farming, biocontrol agents, and integrated pest management offer promising solutions (Ismaila *et al*., 2023). By minimizing environmental impact and enhancing crop resilience, these practices can ensure food security, economic stability, and a sustainable future for the banana industry.

Despite extensive knowledge of Foc, significant gaps remain in understanding its biogeography and the agro-environmental factors influencing its spread. This study aims to address this gap by investigating the biogeography of Foc in banana-growing regions, focusing on the relationships between soil, climate, and agro-environmental factors with Foc epidemiology. By filling this knowledge gap, we can develop more effective FW management strategies and ensure the sustainability and resilience of the banana industry.

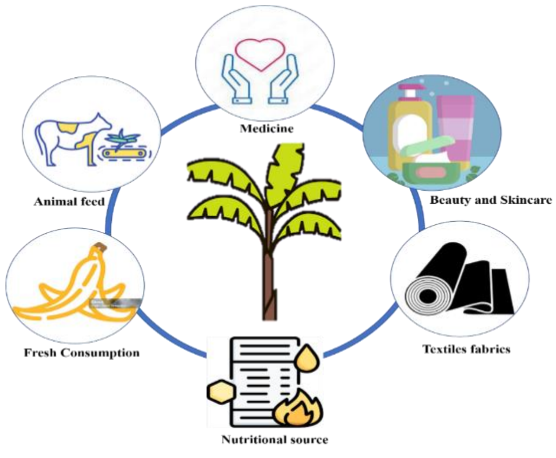

Fig. 1: Exploring the multifaceted applications and versatile utilization of bananas in various industries and everyday life

The Nutritional Brilliance of Banana

Banana is considered a nutritional powerhouse, offering a diverse array of health benefits, making them an invaluable component of a balanced diet. Rich in essential nutrients, these yellow fruits are particularly noteworthy for their role as a superior dietary fiber source, promoting digestive health and preventing constipation. Consuming dietary fiber has been linked to a lower chance of colorectal cancer, lowered cholesterol levels, normalized blood sugar, and effective weight management (Raymond and Seed, 2017). Beyond their fiber content, bananas serve as an excellent energy source, as demonstrated by research indicating that one can get enough energy for a 90 min workout by eating two bananas (Kumar *et al.*, 2012). Athletes prioritize bananas due to their unique blend of vitamins (Vitamin B6, Vitamin C) and minerals (potassium, copper, manganese), making them a reliable fruit for preventing muscle cramps (Mateljan, 2007). Enzymes like amylase and maltase in bananas aid in the breakdown of complex carbohydrates, further contributing to their nutritional value (Brady, 2023). Carbohydrates, a major energy source, are present in ripe bananas with about 15g of total sugar, resulting in a low Glycemic Index (GI) value. Roughly 26.95 g, or 12% of the dietary reference intake, is found in a typical-sized banana. (DRI) (Mateljan, 2007). While bananas may not be a rich source of proteins compared to other protein sources, a normal-sized banana still provides a sufficient amount, offering about 1.2 g of protein and serving 2% of the DRI (Mateljan, 2007). As fruits and vegetables are known for their antioxidant properties, bananas contain various antioxidants, including flavonoids and amines, associated with reduced risks of heart disease and macular degeneration (Rose-Francis and Bjarnadottir, 2023). Banana emerges as a significant source of potassium, with a normal-sized banana providing 350 mg (Fig. 2). One banana provides approximately 23% of the daily potassium needed, which is a vital mineral involved in many body activities (Kumar *et al*., 2012).

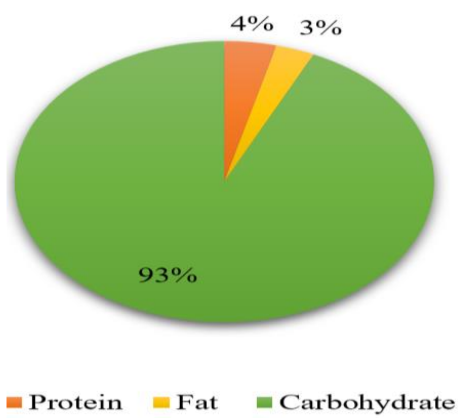

Fig. 2: Source of calories of banana

While bananas may not be a primary source of calcium, they still contribute, offering about 5.9mg of calcium per normal-sized banana, serving 1% of the DRI (Mateljan, 2007). Manganese, an important micronutrient with antioxidant properties, is found in fresh bananas, serving as an antioxidant enzyme's cofactor such as Manganese Superoxide Dismutase (MnSOD) (Marmion, 2014; Dhar and Clair, 2012). Banana also contains Vitamin C, albeit not in substantial amounts. The Dwarf Brazilian Banana, for instance, has an average content of about 12.7 mg of Vitamin C per 100 g, three times more than Williams Fruit (Wall, 2006). Vitamin B complex, essential for cell metabolism, is present in bananas, making them a reliable source of these water-soluble vitamins (Kaur, 2015).

Bananas are a versatile and nutrient-rich fruit that contributes to overall health and well-being by providing a balanced combination of carbohydrates, vitamins, and minerals. Incorporating bananas into a well-rounded diet is a simple and effective way to harness their numerous nutritional benefits (Table 1).

Table 1: The nutritional composition of banana

Constituents	Amount/value (100 g)	Unit
Basic nutritional composition		
Water	74.9	G
Energy	371	kJ
Carbohydrate, by difference	22.8	G
Protein	1.09	G
Total lipid (fat)	0.33	G
Fiber, total dietary	2.6	G
Total Sugars	12.2	G
Starch	5.38	G
Sucrose	2.39	G
Glucose	4.98	G
Fructose	4.85	G
Lactose	0	G
Maltose	0.01	G
Galactose	0	G
Mineral composition		
Calcium, Ca	5	Mg
Magnesium, Mg	27	Mg
Potassium, K	358	Mg
Sodium, Na	1	Mg
Phosphorus, P	22	Mg
Iron, Fe	0.26	Mg
Zinc, Zn	0.15	Mg
Copper, Cu	0.078	Mg
Manganese, Mn	0.27	Mg
Fluoride, F	2.2	µg
Vitamin composition		
Vitamin C, total ascorbic acid	8.7	Mg
Thiamin	0.031	Mg
Riboflavin	0.073	Mg
Niacin	0.665	Mg
Pantothenic acid	0.334	Mg
Vitamin B-6	0.367	Mg
Folate, total	20	µg
Folic acid	0	µg
Vitamin B-12	0	µg
Vitamin A, RAE	3	µg
Retinol	0	µg
Carotene, beta	26	µg
Carotene, alpha	25	µg
Vitamin A, IU	64	IU
Vitamin E (alpha-tocopherol)	0.1	Mg
Vitamin D (D2 + D3)	0	µg
Vitamin K (phylloquinone)	0.5	µg
Vitamin K (Dihydrophylloquinone)	0	µg

Source: USDA (2019)

Fusarium Wilt of Banana: Causal Agent and Geographical Distribution

Fusarium wilt of banana, a devastating disease caused by the soil-borne fungus *Fusarium oxysporum* f.sp. *cubense* (Foc), significantly impacts global banana production across diverse cultivars with varying susceptibility. This pathogen reproduces through macroconidia, chlamydospores, and microconidia, with its chlamydospores being particularly resilient, featuring a double membrane that allows the fungus to persist in soil for long periods without a host (Nelson, 1991). This persistence renders soil previously inhabited by infected plants unsuitable for the replanting of susceptible cultivars, posing a major challenge for banana cultivation (Davis, 2005).

The fungus is divided into three primary races based on their host range and virulence: Race 1 (R1), Race 2 (R2), and Race 4 (R4), with further distinction into various Vegetative Compatibility Groups (VCG) within each race (Dita *et al*., 2018; Ploetz, 2006). R1 has been responsible for epidemics affecting 'Gros Michel' and other varieties, while R2 targets the 'Bluggoe' subgroup. R4, particularly its variant Tropical Race 4 (TR4), is the most virulent, impacting a wide range of banana groups including the widely cultivated Cavendish variety. Foc's origin traces back to Southeast Asia, where it co-evolved with the Musaceae family, spreading to banana-producing regions worldwide except for a few areas like Somalia, the southern Pacific Islands, and the Mediterranean Basin's riparian nations. The most pathogenic race, Foc R4, is further classified into tropical (TR4) and subtropical (SR4) races, with TR4 posing significant risks in both subtropical regions such as Australia, Taiwan, South Africa, and the Canary Islands and tropical regions including Southeast Asia (Dita *et al*., 2018; Ploetz, 2006; 2015; Maryani *et al*., 2019; Buddenhagen, 2009; García-Bastidas *et al*., 2014; Molina *et al*., 2009). Foc's geographical distribution is extensive, affecting continents like Asia, Africa, Australia, and the Americas.

In Asia, Fusarium wilt has been reported in countries such as Laos, Vietnam, Bangladesh, Cambodia, Sri Lanka, Indonesia, Malaysia, the Philippines, mainland China, and Taiwan, with TR4 causing significant losses, particularly in Cavendish cultivation settings (Chittarath *et al*., 2022; Mostert *et al*., 2017). India's Grand Naine cultivar and the local Rasthali variety have also suffered substantial yield reductions, with regions like Tamil Nadu's Thoothukudi district experiencing up to 50-60% yield losses (Vijayasanthi *et al*., 2022).

In Africa, Fusarium wilt poses a threat to banana production in Kenya, Burundi, the Democratic Republic of Congo, Rwanda, Tanzania, and Uganda. The disease not only jeopardizes the agricultural economy but also food security in these regions, where bananas serve as both cash crops and staple foods (Momanyi *et al*., 2021; Mostert *et al*., 2018; van Westerhoven *et al*., 2022).

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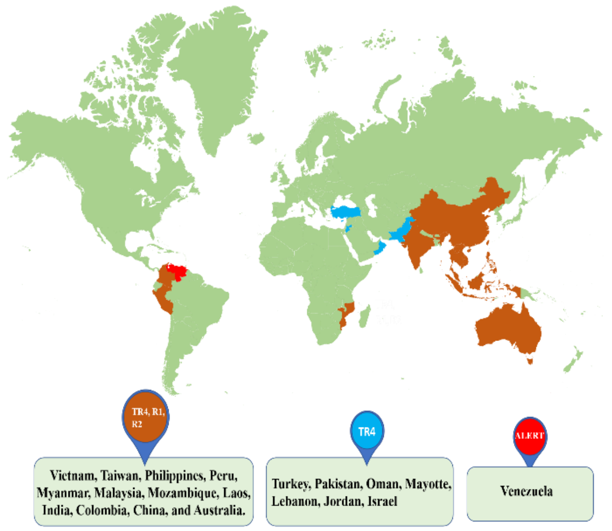

Fig. 3: Geographical distribution of *Fusarium oxysporum* f.sp. *cubense* (Foc) races

The detection of Foc TR4 outside commercial farms in Mozambique underscores the disease's potential to further spread within the continent (Van Westerhoven *et al*., 2023).

Latin America and the Caribbean, crucial players in the global banana export industry, have witnessed FWB outbreaks, particularly of the TR4 strain, in countries such as Colombia, Peru, and Venezuela. These outbreaks pose a significant risk to the Cavendish variety, which dominates the export market, raising concerns about the industry's future sustainability and the livelihoods of those reliant on banana farming (Mejías Herrera *et al*., 2023; Martínez de la Parte *et al*., 2024).

Australia has been battling Fusarium wilt since 1874, with TR4 leading to the collapse of the Cavendish industry in the Northern Territory and spreading to northern Queensland. This situation highlights the disease's ability to adapt and circumvent regional biosecurity measures, impacting both export varieties and local favorites like Lady Finger and Ducasse (Pegg *et al*., 2019) (Fig. 3).

The global challenge of Fusarium wilt underscores the need for international cooperation, increased investment in research and development of resistant cultivars, and the adoption of improved agricultural and biosecurity practices. Addressing this threat is vital for securing the future of banana cultivation worldwide, protecting food security, and sustaining the economies of banana-producing regions.

Identification and Diagnosis of Fusarium Wilt in Banana Plants: External and Internal Symptomatology

Banana plants afflicted with Fusarium wilt exhibit distinct symptoms, primarily characterized by the noticeable yellowing and wilting of older leaves, ultimately leading to the demise of affected plants. While external manifestations, such as leaf yellowing and wilting, are indicative, it is crucial not to rely solely on these outward signs for identification. Various biotic factors like bacterial wilt, Armillaria, and banana weevil, as well as abiotic stresses, including nutrient deficiency and water-logging, can induce similar symptoms in banana plants. Therefore, a comprehensive diagnosis of Fusarium wilt in suspected plants necessitates the examination of internal symptoms within the pseudostem and rhizome, along with the isolation of *Fusarium oxysporum* f.sp. *cubense* (Foc) from affected tissue (Viljoen *et al*., 2017).

External Symptoms

The hallmark symptom of banana Fusarium wilt is chlorosis, primarily observed as yellowing in older leaves, typically starting at the leaf margins and progressing toward the midriff. In specific banana varieties, such as Foc TR4-affected Cavendish banana, chlorosis is succeeded by necrosis, resulting in leaf tissue death. Conversely, in Pisang Awak, browning of affected leaves is less common. Irrespective of the variety, two consistent indicators of Fusarium wilt are the upward progression of symptoms from mature to younger foliage and the bending and drooping of petioles on affected leaves. Another external symptom often associated with Fusarium wilt is splitting the pseudostem. However, pseudostem splitting may not always be exclusive to Fusarium wilt and should be considered alongside leaf yellowing and wilting in suspect plants (Viljoen *et al*., 2017).

Internal Symptoms

Fusarium wilt induces distinctive inner symptoms in the pseudostem and rhizome, regardless of the type of banana that is impacted. Longitudinal slicing of wounded pseudostems reveals reddish-brown lesions within the leaf bases. These lesions progress through the vascular tissue and longitudinal splitting of pseudostems aids in clearly visualizing their development. Early infections are characterized by light yellow to reddish discoloration, confined to the vessels of the xylem, providing optimal material for Foc isolation. With aging, lesions expand and darken, potentially co-colonized by secondary contaminants. Confirming the continuity of lesions distinguishes those caused by Foc from other biotic stresses. Rhizome inspection becomes crucial when external symptoms are present but internal symptoms are absent in pseudostems. Diseased plants exhibit distinctive darkening in the inner rhizome that ranges from light yellow to brownish color and typically begins at the margins and moves inside. Partial or complete inner rhizome involvement occurs with disease progression, while the outer rhizome remains unaffected. In cases where no discoloration is observed, black spots on the inner rhizome indicate a cause other than Foc (Viljoen *et al*., 2017) (Fig. 4).

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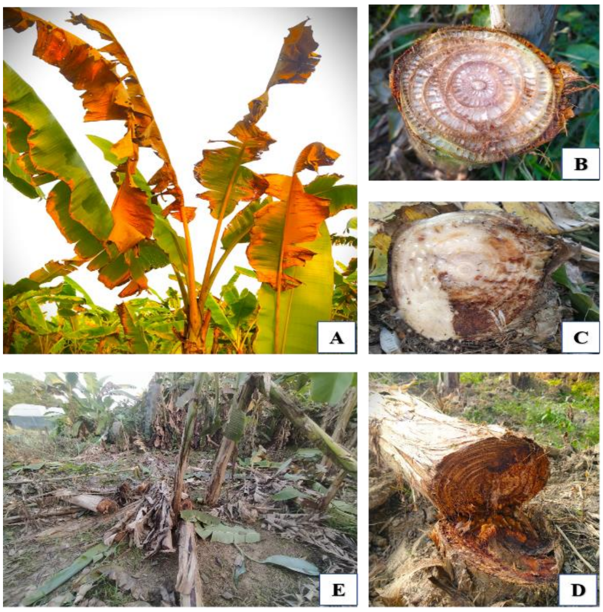

Fig. 4: Fusarium Wilt Symptoms in Banana Plants: (A) Yellowing of leaf margin; (B) Initial; (C) Moderate; (D) Advanced vascular discoloration of pseudostem; (E) Field destroyed by Foc infestation

Fusarium wilt in banana presents distinct symptoms including leaf yellowing, pseudostem and vascular tissue discoloration, and pseudostem splitting (Zhan *et al*., 2022). These characteristic manifestations serve as key identifiers of Fusarium wilt, aiding in its differentiation from other plant diseases. In certain instances, specialized diagnostic tools such as Raman spectroscopy can be employed to detect FOC infection during the asymptomatic stage, offering a dependable and non-destructive means for early detection and diagnosis of Fusarium wilt in bananas (Parlamas *et al*., 2022).

Fusarium Wilt Dynamics in Banana Farms: Spread, Challenges and Potential Vectors

Banana Fusarium wilt exhibits a "polycyclic" nature, in contrast to the "monocyclic" Fusarium wilt of cotton described by Van der Plank (1963), which manifested throughout a single season from isolated pockets of soilborne inoculum. In banana farms affected by Fusarium wilt, multiple infection cycles occur, leading to significant consequences even with minimal pathogen infestation initially, as observed in the unchecked TR4 epidemics in China and the Philippines (Buddenhagen, 2009).

The challenges in cultivating "Gros Michel" in previously affected farms are highlighted by Stover (1962), who also emphasized the longevity of *Fusarium oxysporum* f.sp. *cubens* (Foc) in infected soil. Since chlamydospores were discovered in the dead host material and could infect non-host weed species, rotations devoid of bananas were frequently unsuccessful. The spread of Foc occurs through various means, including the use of infected suckers, as noted by Stover (1962). Tissue-culture plantlets provided a breakthrough in creating pathogen-free plantations, but secondary contamination of plantations remained a common occurrence, such as in TR4-affected Cavendish plantations. Contamination through surface waters, particularly river or pond water used for irrigation, is a significant risk. Additionally, items such as clothing, footwear, and farm implements can serve as vectors for Foc, as Stover (1962) emphasized. Further exacerbating the spread of Foc are practices such as trading asymptomatic yet infected banana planting materials, the transportation of machinery carrying soil remnants, and the utilization of traditional banana-based packaging (Warman and Aitken, 2018; Dita *et al*., 2013). Moreover, the pathogen can infiltrate the plant through the rhizome, affecting various parts including the roots, rhizome, and outer leaf sheaths of the pseudo stem. Within the non-senescing leaf sheaths, Foc can migrate through the xylem vessels, encompassing both visibly discolored vascular tissue and healthy ones (Bermúdez-Caraballoso *et al*., 2020). As leaf sheaths undergo senescence, chlamydospores develop within gas spaces, while sporodochia formation and hyphal growth manifest on the outer surface of senescing leaf sheaths (García-Bastidas *et al*., 2019). These pathways underscore the critical importance of implementing on-farm hygiene and biosecurity protocols to curb the spread of Foc and effectively manage incursions of Fusarium wilt.

Several routes, including those mentioned above, facilitate the movement of Foc within and around plantations. The banana weevil *Cosmopolites sordidus* has recently been identified with TR4 on its exoskeletons, suggesting its potential role as a disease vector or predisposing factor (Meldrum *et al*., 2013). Additionally, the development of macroconidia/sporodochia on artificially infected plants in greenhouse tests a characteristic seen in other *Fusarium oxysporum formae* speciales, notably in greenhouses indicates the viability of aerial dispersion of Foc (Gullino *et al*., 2012; Timmer, 1982).

Disease Cycle of Fusarium oxysporum f.sp. cubense (Foc)

The saprophytic nature of *Fusarium oxysporum* f.sp. *cubense* (Foc) enables its chlamydospores to persist in soil for several decades (Yadeta and Thomma, 2013). These fungal spores, specifically chlamydospores, adhere to root caps in the soil and subsequently undergo germination to establish colonization around the surface of the host root.

Foc invades the epidermal cells of the tiny lateral roots by either breaking through the cell wall directly or by penetrating through wound or damage sites in the roots. Once within the root system, the hyphae penetrate intercellular and intracellularly, progressing to invade the cortex tissue and pass the endodermis. The hyphae then get to the vessels of the xylem, moving acropetally through the cell sap (Yadeta and Thomma, 2013) (Fig. 5).

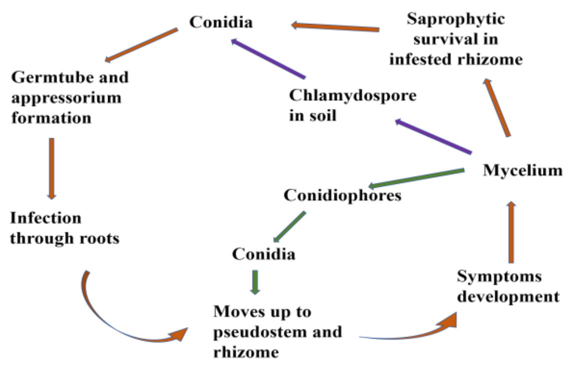

Fig. 5: Disease cycle of *Fusarium oxysporium* f.sp. *cubense*

The host plant wilts as a result of the xylem vessels' intense mycelial growth and sporulation, which reduce the effectiveness of water absorption. The Cavendish cultivar's gel deposition or the Gold Finger (FHIA 01) variety's strong lignification limits the passage of Foc in xylem vessels in cultivars that are resistant to Foc race 1 (Mace, 1963; Van den Berg, 2006). Infected plants display characteristic yellowing of mature leaves, followed by gradual withering and ultimately the death of the host plant. Moreover, Strong phytotoxins such as fusaric acid released by Foc during infection exacerbate plant cell death (Laluk and Mengistea, 2010).

Banana plants release H_2O_2 and protective enzymes such as catalase, superoxide dismutase, peroxidases, and polyphenol oxidases in response to Foc infection (Thakker *et al*., 2013). By feeding on dead plant components such as leaves, pseudostems, and roots, the fungus continues to exist saprophytically. It also develops a lot of resting spores that are assimilated into the soil flora. For three to four decades, chlamydospores in the soil can spread and cause wilt outbreaks in recently planted vulnerable banana varieties.

Factors Influencing Fusarium Wilt Outbreaks in Banana: Biotic and Abiotic Determinants

Various biotic and abiotic factors can either accelerate or impede the occurrence of Fusarium Wilt (FW) outbreaks, leading to *Fusarium oxysporum* f.sp. *cubense* (Foc) epidemics. Key contributors to these epidemics include host resistance, pathogen aggressiveness, and the plant's developmental stage (Brake, 1991). Moreover, Furthermore, weather factors including extended wet or dry spells, temperature swings, storm damage, and soil properties like aeration and drainage have a huge impact on the disease's severity (Brake *et al*., 1995). Abiotic factors play a crucial role in FW outbreaks. Weather conditions affect the severity of FW during infection, systemic vascular infection, and the onset of wilt symptoms (Cook *et al*., 1981). Dry conditions of soil facilitate the survival of pathogens in the root zone, with disease progression contingent on water availability for pathogen growth and dispersion in xylem fluid post-infection (Fig. 6).

Temperature, identified by Rishbeth (1957) and Stover (1962), is pivotal in FW development. Peng *et al.* (1999) found the pathogen's optimum temperature for development to be 28°C, inhibited above 33°C and below 17°C. Poorly drained soil increases wilt prevalence, especially when the root zone is temporarily flooded (Rishbeth, 1957; Stover, 1962). Soil flooding leads to hypoxia or anoxia, restricting banana roots' oxygen access and increasing susceptibility to infection (Aguilar *et al*., 2000). Well-aerated and well-drained soils are generally considered to minimize FW through enhanced microbial activity and root growth (Stover and Simmonds, 1987). Conversely, compacted soils with reduced aeration may benefit FW (Domínguez *et al*., 2001).

Biotic factors, such as external elements causing root damage, can facilitate Foc infections, particularly when entering through wounds. Plant-parasitic nematode attacks, like *Radopholus similis*, may exacerbate FW outbreaks (Somu, 2012; Dinesh *et al*., 2014). However, the interaction's impact may vary based on cultivar resistance (Chaves *et al*., 2014). Weevil attacks, such as *Cosmopolites sordidus* and *Metamasius hemipterus*, might predispose plants to FW, but further research is needed to confirm their role. Soil suppressiveness, linked to active and diverse microbiota, is believed to reduce FW (Doran *et al*., 1996). A suppressive soil harbors low disease levels despite a susceptible host, pathogen, and favorable environmental conditions. Suppressive soils are enriched in specific bacterial species, such as *Chthonomonas* spp., *Pseudomonas* spp., and *Tumebacillus* species (Xue *et al*., 2015). Recent studies also highlight the positive role of *Gammaproteobacteria*, *Pseudomonas*, and *Stenotrophomonas* species in healthy plants (Köberl *et al*., 2017). Understanding these factors is crucial for effective FW management strategies (Table 2).

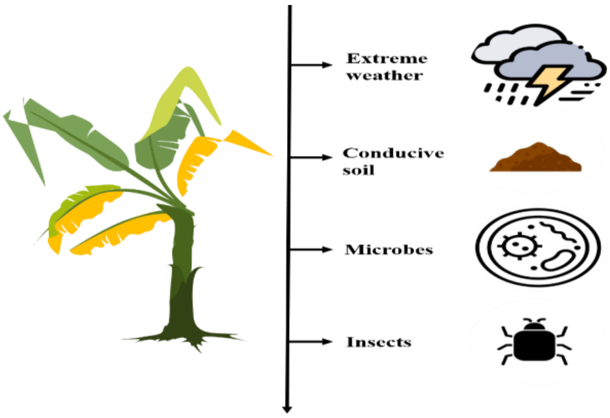

Fig. 6: Unveiling factors behind Fusarium wilt outbreaks in banana

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Table 2: Agro-environmental factors favor the incidence of *Fusarium oxysporum* f.sp. *cubense* (Foc)

Factors	Description	References
Climatic conditions		
Temperature	Favorable temperature ranges from 23-29°C, with optimum at 25°C	Groenewald *et al.* (2006)
Precipitation	Water excess: Poorly drained soils with heavy textures	Lahav and Israeli (2019)
Physical properties of soil		
Texture	Sandy texture (low pH)	Deltour *et al.* (2017)
Slope	Convex curvature slope	
Distribution of the size of aggregates	<0.053 mm	Li *et al.* (2018)
Chemical properties of soil		
Ph	7.5–8.5	Brake *et al.* (1995)
Acidity	Ph of 5.1 favors the growth of Foc.	Segura-Mena *et al.* (2021)
Phosphorus	Concentration < 20 mg/L	
Magnesium	7.9–10.6 cmol/kg	Gutiérrez Jerez *et al.* (1983)
Potassium	High FW incidence is correlated with potassium deficits.	Huber *et al.* (2012)
Biological properties of Soil		
Nematodes	High presence of plant parasites (Meloidogynidae, Hoplolaimidae, Pratylenchidae, and Rotylenchulidae) and bacterivorous nematodes (Rhabditidae, Pangrolaimidae and Cephalobidae)	Zhong, *et al.* (2011)
Bacteria	Increase of enterobacteriaceae	Köberl *et al.* (2017)
Crop management		
Bare soil	Averaging 30.13% of bare soil	Pattison *et al.* (2014)
Distance between plants	<3.0 m	
Chicken manure	Increases the Foc inoculum	Nasir *et al.* (2003)

Economic Impacts of Fusarium Wilt on the Global Banana Industry

Fusarium wilt, caused by the *Fusarium oxysporum* f.sp. *cubense* (Foc) fungus, presents a formidable threat to global banana cultivation, with a particular strain on the primary export variety, Cavendish (Mejías Herrera *et al.*, 2023). This disease imposes substantial economic burdens on both the production and consumption sectors of the banana industry. Annually, it accounts for the loss of 950,000 metric tonnes of bananas due to *Fusarium oxysporum* infection (Waraczewski and Sołowiej, 2022; Niwas *et al.*, 2022). These losses equate to 60-90% of banana production worldwide and 30-40% in India, with specific cultivars such as Rasthali in Tamil Nadu experiencing reductions in yield by 50-60% (Vijayasanthi *et al.*, 2022; Waraczewski and Sołowiej, 2022). The disease's presence in Venezuela, a nation heavily reliant on domestic banana production, coupled with its detection in Colombia, Peru, and other regions across Latin America and the Caribbean comprising 75% of the world's banana exports has heightened global apprehension (Mejías Herrera *et al.*, 2023; Niwas *et al.*, 2022).

Managing Fusarium wilt can be quite expensive for farmers, as it involves measures such as soil fumigation, crop rotation, and cultivating resistant banana varieties. These measures can increase production costs and reduce profitability for farmers, which can threaten the sustainability of banana farming. Studies have shown that implementing comprehensive disease management strategies can yield Internal Rates of Return (IRR) of 11-14% (De Figueiredo Silva *et al.*, 2023). Delayed adoption of gene-edited bananas resistant to Fusarium wilt could lead to economic losses of $94 billion over five years (Heck *et al.*, 2021).

The impact of the disease goes beyond just reducing production levels. It can also have an adverse effect on exports from affected regions, leading to job losses, particularly in rural areas, and ultimately, increasing poverty levels. A reduction in banana availability can also lead to a surge in prices, making it difficult for consumers to afford. Therefore, it is crucial to develop a comprehensive strategy that includes both immediate and long-term interventions to mitigate the economic fallout of Fusarium wilt on the banana industry.

Sustainable Management Strategies for Fusarium Wilt in Banana Plantations

Management strategies for Fusarium wilt in banana plants are crucial for safeguarding global banana cultivation. These strategies, including crop rotation and intercropping, organic amendments, cover crops, silicon and borax application, phytohormones, bio-control agents, and transgenic approaches, contribute to disease control and sustainable farming practices (Fig. 7).

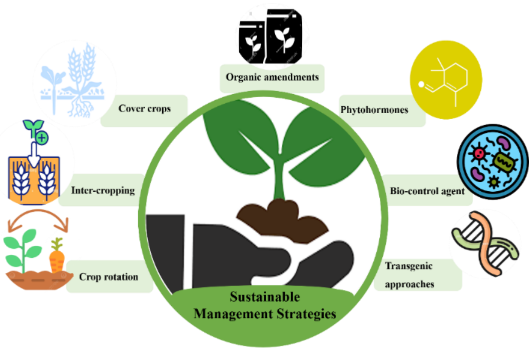

Fig. 7: Sustainable approaches for the management of Fusarium wilt in banana

Effective implementation can reduce the severity of infections and enhance soil health. These strategies provide holistic solutions, addressing biotic and abiotic factors and ensuring long-term resilience against Fusarium wilt. The importance lies in sustaining banana production, protecting livelihoods, and promoting a resilient and disease-resistant agricultural ecosystem.

Crop rotation and Inter-Cropping

Crop rotation and intercropping are essential agricultural practices, playing a significant role in soil pathogen control and modifying microbial environments. A noteworthy example of this strategy is observed in banana plantations, where the rotation of crops such as paddy, sugarcane, cassava, and cereals has been identified as an effective measure (Buddenhagen, 2009). Research by Su (1986) suggests that a rotation involving paddy cultivation for 3-4 years proves particularly effective in managing wilt-infested soils.

Furthermore, Chinese leek emerges as a viable and ecologically friendly treatment for combating Fusarium wilt in banana crops, showcasing a remarkable reduction in infestation rates ranging from 88-97%. This innovative approach addresses the disease and contributes to the overall sustainability of agricultural practices (Deltour *et al*., 2017). Additionally, managing ground cover at the base of banana plants plays a crucial role in diminishing the frequency and severity of diseases. Studies conducted by Pattison *et al.* (2014) emphasize the significance of ground cover management as a vital component in disease prevention strategies within banana plantations.

In summary, the integration of crop rotation, intercropping, and effective ground cover management represents a holistic approach to addressing soil-borne pathogens, enhancing soil microbial health, and sustainably managing crop diseases in agricultural systems (Buddenhagen, 2009; Su, 1986; Deltour *et al*., 2017; Pattison *et al*., 2014).

Organic Amendments

Sustaining soil health and strengthening resistance to pathogens depend heavily on the efficient management of organic matter. Organic Amendments (OAs) can be selectively administered at different doses and specific places, such as disease hotspots, to maximize their impact. A study conducted by Yogev *et al*. (2006) demonstrated the disease-suppressing capabilities of composts derived from plant-waste residues. These composts effectively mitigated diseases developed by four distinct formae speciales of *F. oxysporum: basilici, melonis, radicis-cucumerinum,* and *radicis-lycopersici.*

Furthermore, integrating beneficial microbes with organic amendments enhances the ability to control Fusarium Wilt (FW) in banana plants. This synergistic approach can be characterized as biological control. Notably, competition for nutrients arises between *F. oxysporum* and other beneficial pathogens, as observed by Hadar and Papadopoulou (2012). However, caution is warranted, as negative effects may also manifest. For instance, chicken manure has been found to accelerate the incidence of FW in banana plants under greenhouse conditions, as reported by Nasir *et al.* (2003); Pittaway *et al.* (1999). This phenomenon is not limited to controlled environments, as similar observations have been made in field conditions in Brazil. In such cases, the improper decomposition of chicken manure leads to root damage, reduced soil pH, and nitrogen source imbalance, acting as predisposing factors for Fusarium wilt (Nasir *et al*., 2003).

Cover Crops

Using cover crops, often known as ground cover, is still acknowledged as a beneficial agricultural technique for controlling weeds, pests, and illnesses and increasing crop productivity (Djigal *et al*., 2012; Pattison *et al*., 2014). Despite the acknowledged benefits of cover crops, a limited body of research specifically addresses their impact on Fusarium Wilt (FW). Pattison *et al*. (2014) conducted a study highlighting the efficacy of Pinto peanut (*Arachis pintoi*) as a ground cover, demonstrating a noteworthy 20% reduction in Fusarium wilt intensity in Ducasse banana (*Pisang awak*). Moreover, the authors observed a positive correlation between ground cover and increased bunch weight, further contributing to enhanced yield.

Although this research suggests promising outcomes, it is important to note that the effectiveness of cover crops in controlling Fusarium wilt in bananas is not universally established. The evidence supporting cover crops as a comprehensive solution for Fusarium wilt management remains inconclusive to date. Continued research and comprehensive studies are warranted to determine the broader applicability and reliability of cover crops in effectively mitigating Fusarium wilt and improving overall banana crop health.

Application of Silicon (Si) and Borax (H_3BO_3)

Utilizing Silicon (Si) and borax (H_3BO_3) in agriculture has demonstrated significant efficacy in mitigating the intensity of various infections in specific crops. Notably, the application of silicon has been shown to suppress diseases in cucurbits caused by both foliar and soil-borne pathogens. The enhanced resistance against fungal pathogens observed in Si-amended plants is attributed to leaf silicon accumulation (Niwas *et al*., 2019).

Seven micronutrients were examined in research by Niwas *et al.* (2019), including calcium nitrate, copper sulfate, zinc sulfate, ammonium sulfate, ferrous sulfate, potassium chloride, and borax. It was observed that borax at a concentration of 500 ppm exhibited total suppression of the growth of *F. oxysporum* f.sp. *cubense*, surpassing the inhibitory effect of zinc sulfate. Similar findings were reported by Johnson *et al.* (2003) regarding the control of stem rot in groundnut. The positive impact of micronutrients, including borax, on plant health is attributed to their role in enhancing soil fertility and promoting overall plant vigor. The micronutrients contribute to a robust plant immune system, reducing disease susceptibility. The study revealed that the mycelial growth of *F. oxysporum* f.sp. *cubense* was significantly restrained when exposed to various micronutrients, emphasizing the potential of borax and other micronutrients in disease management. This underscores the importance of micronutrient supplementation for achieving a disease-resistant and thriving crop ecosystem.

Application of Phytohormones

Applying phytohormones, also called plant hormones, plays a vital role in enhancing plant defense mechanisms and providing resistance against both biotic and abiotic stressors. One notable phytohormone is Methyl Jasmonate (MeJA), which stimulates host defense against a diverse range of infections and regulates the plant's defense responses to various biotic and abiotic challenges. Research conducted by Sun *et al.* (2013) revealed that MeJA, upon inoculation with Foc-TR4, induced the activity of enzymes while concurrently reducing the levels of hydrogen peroxide (H_2O_2) and Malondialdehyde (MDA) in banana plants. The observed activation of genetic resistance to Foc-TR4 by MeJA was attributed, in part, to the enzymatic processes facilitated by MeJA. Additionally, Salicylic Acid (SA) emerges as another significant phytohormone with the capacity to trigger the immune system of plants, as highlighted by An and Mou (2011). Wang *et al.* (2015) further emphasized the crucial role of SA in plant-microbial interactions and its function in conferring resistance to Foc-TR4 in banana plants. The research findings underscore the multifaceted impact of phytohormones like MeJA and SA, enhancing defense mechanisms and orchestrating specific enzymatic activities that contribute to the plant's resilience against various stressors.

Bio-Control Agent

Biocontrol agents (BCAs) have emerged as a promising strategy for disease control, particularly in the case of Fusarium wilt in banana crops. Despite the effectiveness of BCAs, their longevity in the field has been observed to be relatively short. Numerous pieces of research have demonstrated the impact of soil microflora and chemical and physical edaphic variables on the effectiveness of biocontrol against Fusarium wilt (Scher and Baker, 1980; Weller *et al.*, 2002). For the healthy antagonistic microbial community that suppresses illness, chemical and physical factors including pH, organic matter content, aeration, water potential, soil texture, and cation availability are essential. The microflora present in the rhizosphere contribute to preventing Panama disease by outcompeting *Fusarium oxysporum* f.sp. *cubense* (Foc) for vital minerals and plant surface adhesion points. Additionally, microorganisms in the rhizosphere may produce secondary metabolites or enzymes and induce systemic plant defense responses (Scher and Baker, 1980; Papavizas, 1985; Wu *et al*., 2013). Various antagonistic fungi, including *Trichoderma, Aspergillus, Penicillium*, and antagonist bacteria such as *Bacillus* and *Pseudomonas*, are prevalent in the wilt-free banana rhizosphere. However, their abundance decreases significantly in the rhizosphere of wilt-affected banana plants (Ghag *et al*., 2015). Actinomycetes, specifically *Streptomyces*, have been isolated from infected and uninfected banana tissues, with a higher percentage found in healthy roots than infected ones (Cao *et al*., 2004). To mitigate Fusarium wilt disease incidence, transforming conducive soil into suppressive soil by introducing microorganisms from suppressive soil has been proposed (Weller *et al*., 2002). Unfortunately, there is a lack of available data regarding Fusarium wilt-suppressive soil specific to bananas. *Trichoderma* species have proven to be effective as microbial agents in shielding plants from soil-borne infections, such as Fusarium wilt, by causing the host plant to develop a resistance to the pathogen. Field trials have shown that soil application of *Trichoderma harzianum* can effectively control Fusarium wilt, comparable to the fungicide carbendazim. Other antagonistic fungi, such as *Streptomyces* and *Penicillium*, when allowed to colonize banana plant roots, have also shown significant suppression of wilt disease (Getha *et al*., 2005; Ting *et al*., 2012).

Furthermore, arbuscular mycorrhiza has been identified as a factor capable of reducing disease severity in plants infected with *Fusarium oxysporum* (Smith, 2006). These findings collectively underscore the potential of biocontrol agents, particularly specific fungi and bacteria, in managing Fusarium wilt in banana crops (Table 3). Continued research and exploration of microbial dynamics in the rhizosphere and soil could further enhance our understanding and application of biocontrol strategies in agricultural practices.

Transgenic Approaches

Biotechnological approaches have emerged as a promising avenue for developing resistant banana varieties in response to the challenges presented by conventional breeding methods in banana cultivation. These challenges include the laborious nature caused by the lack of seeds in edible triploid banana cultivars (Bakry *et al*., 2009) and the stagnancy in the gene pool attributed to parthenocarpy. The commercial acceptance of genetically modified bananas remains uncertain, yet it represents a pivotal strategy for overcoming inherent breeding limitations.

Table 3: Compilation of frequently used biocontrol agents targeting Fusarium wilt in banana

Biocontrol agents	Effective against (Foc race)	Application method	Relative remarks	References
Serratia marcescens ITBB B5-1	4	Drenching of soil before planting	Isolated from the rubber trees	Tan *et al*. (2015)
Acremonium sp. Q34	4	Dripping root into the fermentation broth	Separated from a healthy *Kandelia candel*	Li *et al*. (2018)
Bacillus subtilis EPB 10 and EPB 56, *Pseudomonas fluorescens* Pf1	1	Root dipping	Growth-promoting effects	Kavino and Manoranjitham, (2018)
Streptomyces griseorubiginosus S96	4	Root dipping	Strain-producing siderophores, chosen from 131 endophytic actinomycetes found in banana roots	Cao *et al*. (2005)
Fusarium oxysporum BRIP 29089, 29093, and 45952	1, STR4	Colonized ground millet	Derived from the roots of bananas in soil with suppressive properties	Forsyth *et al*. (2006)
Penicillium citrinum	4	Soil drenching	Response of the host defense	Ting *et al*. (2012)
Trichoderma sp. TJ5	1	Dipping of root	Promotion of plant growth	Hernández *et al*. (2014)
Trichoderma harzianum	4	Soil inoculation	*T. Harzianum* + Ca $(NO3)_2$	Ting *et al*. (2003)
Trichoderma asperellum PZ6	4	Root-damage irrigation technique	Plant growth promotion	Qin *et al*. (2017)
Pseudomonas fluorescens Pfcp	1,4	Dipping of root	Less severe interior browning and wilting	Sivamani and Gnanamanickam (1988)
Pseudomonas fluorescens Pf10	1	Soil drenching	Phenolics and Defense enzyme induction	Thangavelu *et al*. (2003)
Bacillus subtilis KY-21	4	Soil drenching	Defense-related enzymes are stimulated	Sun *et al*. (2011)
Burkholderia cenocepacia 869T2	4	Root dipping	Promotion of growth	Ho *et al*. (2015)
Glomus mosseae, *Trichoderma harzianum*	1	Inoculation at transplanting	Promotion of Growth	Mohandas *et al*. (2010)

The genetic diversity of bananas has seen minimal alteration over generations due to the constraints imposed by parthenocarpy, significantly limiting the potential for conventional breeding (Bakry *et al*., 2009). Consequently, transgenic approaches have garnered attention as a viable solution to introduce resistance traits into banana cultivars. However, the reception of genetically modified bananas in the marketplace remains an open question. Various transgenes have been subjected to experimental scrutiny, with greenhouse or incubator studies typically providing short-term insights. Notably, when addressing the challenges posed by the destructive Panama disease caused by *Fusarium oxysporum*, race-one field trials have yielded limited documented results (Ghag *et al*., 2012; Paul *et al*., 2011; Subramaniam *et al*., 2006). Similarly, the outcomes of field trials assessing resistance to Tropical Race 4 (TR4) are often inadequately reported (Hu *et al*., 2013; Mahdavi *et al*., 2012; Yip *et al*., 2011).

Examining past research, a noteworthy instance from nine years ago highlights a TR4 field trial involving two out of 51 Cavendish transformants expressing the Human Lysozyme (HL) gene, suggesting potential resistance (Pei *et al*., 2005). However, subsequent exploration or validation of these promising lines remains unknown, emphasizing the need for sustained and comprehensive field trials. To determine the sustainability and feasibility of transgenic methods for creating resistant banana varieties and to provide insight into their acceptability and practicality long-term field data are essential.

Future Prospects and Research Directions

The development of resistance to Fusarium Wilt (FW) is mostly dependent on breeding efforts, which means that finding and using novel resistant genotypes will require more funding. The process of creating better diploids may be accelerated by combining traditional methods with state-of-the-art technology like high throughput phenotyping and gene editing. This will greatly advance our understanding of FW resistance. Omics technologies, encompassing genomics, transcriptomics, and proteomics, offer a powerful toolset for unraveling the molecular mechanisms underlying FW. This knowledge is a foundation for developing more precise and effective management strategies.

Exclusion and biosecurity measures must be implemented, with a focus on using only disease-free planting material and limiting the flow of contaminated soil and water. This applies not only to the Tropical Race 4 (TR4) strain but also to more virulent Foc populations globally. As emphasized by Daniells (2011), adherence to quarantine and clean planting material is imperative, even with supposedly resistant varieties. Addressing the impact of climate change on disease dynamics, future research should prioritize developing climate-smart management practices adaptable to changing environmental conditions. Continuous monitoring of Foc populations is essential due to the pathogen's variability and mutational capabilities. Organic amendments, cover crops, and biological agents are examples of practices that improve soil health and have a positive impact on FW control over time. Despite slower action, these practices may provide long-lasting effects, offering additional advantages in pest and disease control (Pattison *et al*., 2014; Haddad *et al*., 2018). However, success is genotype-dependent and linked to FW resistance levels.

Community engagement and knowledge transfer should be a focal point in future research, empowering farmers with information on sustainable management practices. Encouraging widespread adoption is crucial for the long-term success of disease management efforts. Recognizing the global nature of the banana industry and the threat of Fusarium wilt, fostering international collaboration among researchers, institutions and policymakers is vital. Joint efforts can expedite the development and dissemination of effective management strategies on a larger scale.

Conclusion

In conclusion, Fusarium wilt is a serious threat to banana farming globally, affecting food security, livelihoods, and economies across banana-producing areas. This study has carefully outlined the challenges Fusarium wilt presents and has offered innovative ways to manage it. It suggests sustainable farming practices like crop rotation and biological control, alongside exploring genetic engineering for disease-resistant banana strains, as key strategies to combat this disease. Success in combating Fusarium wilt centers on global collaboration among scientists, policymakers, and farming communities to exchange knowledge and enact impactful solutions. Stressing the importance of cooperation, a concerted call for unified action is imperative to devise and execute comprehensive strategies safeguarding banana production. Tackling Fusarium wilt demands a synergistic approach encompassing scientific inquiry, sustainable agricultural practices, and community involvement to secure the longevity of bananas for all. Presently, swift action by decision-makers is crucial to bolster research efforts and implement these strategies effectively, mitigating the repercussions of Fusarium wilt.

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Author’s Contributions

Shanta Adhikary: Drafted, research implementation and data collection.

Mridula Rahman, Mrinmoy Kundu and Md. Al Emran Hosen: Revised and polished the manuscript.

Md. Motaher Hossain: Conceptualization, research designed and drafted.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues are involved.

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