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Plant Diseases: Pathogenicity and integrated management overview

Lobna Hajji-Hedfi [1, 2*], Amira Khlif [1], Wassila Hlaoua[3], Abdelhak Rhouma[1, 2], Samar Dali[1], Omaima Bargougui[1], Hemraj Chhipa[4]

[1] *Regional Centre of Agricultural Research of Sidi Bouzid, Gafsa Road Km 6, B.P. 357, 9100 Sidi Bouzid, Tunisia.*
[2] *Research Laboratory of Agricultural Production Systems and Sustainable Development (LR03AGR02), Carthage University.*
[3] *Higher Agronomic Institute of Chott-Meriem, Sousse University, Sousse, Tunisia.*
[4] *College of Horticulture and Forestry, Jhalawar, Agriculture University Kota, Rajasthan-326023, India.*

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ABSTRACT

Integrated pest and disease management (IPDM) is a strategic approach that combines multiple pest and pathogen control methods to optimize their reduction while minimizing ecological and economic consequences. This multifaceted strategy serves as a fundamental component of sustainable agricultural systems, emphasizing the balanced integration of various methods to achieve effective and environmentally responsible pest and pathogen suppression. Modern agricultural practices, characterized by intensified production and monoculture systems, create optimal environments for pathogen proliferation and virulence. These conditions necessitate the IPDM strategies. Integrated pest and disease management is crucial for mitigating pathogen-induced losses and ensuring sustainable agricultural production. It aims to minimize reliance on chemical fungicides by promoting environment-friendly and economically viable strategies for disease control. This review delves into the major pathogens that affect the plants and the intricate relationship between IPDM and sustainable agriculture, examining the key principles, strategies, and benefits associated with integrating these disease management practices into the agricultural system. It underscores the crucial role of IPDM in minimizing environmental impacts, protecting beneficial organisms, fostering genetic diversity, and ensuring economic sustainability. By adopting integrated pest and disease management strategies, farmers can effectively manage plant diseases while simultaneously safeguarding the long-term health and productivity of their agricultural systems.

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Introduction

Sustainable agriculture applies different methods to minimize its environmental footprint and optimize the utilization of natural resources. This encompasses the reduction of reliance on artificial inputs such as fertilizers and pesticides, improvement of fertility and health of soil, preservation of the biodiversity, and the use of efficient irrigation systems for water conservation. In essence, sustainable agriculture strives to establish a resilient and regenerative food system by achieving a delicate balance between environmental consciousness, economic viability, and social responsibility (Dudek & Rosa 2023).

***Corresponding author Email address**: elhajjilobna@yahoo.fr

Agroecology, also known as sustainable farming, embodies a holistic approach to agricultural production. It seeks to address the world's food needs while simultaneously safeguarding the environment, fostering economic viability, and ensuring social justice. This comprehensive strategy prioritizes resource conservation, long-term ecological balance, and the well-being of both farmers and rural communities. Plant diseases pose a serious threat to global food security and agricultural productivity as they can cause substantial crop damage (Fisher et al. 2012).

Plant diseases are managed through a diversified toolbox of techniques, encompassing cultural practices, biological control, and judiciously applied chemical treatments. Cultural practices, such as crop rotation, meticulous sanitation, and the deployment of disease-resistant cultivars, form the bedrock of disease prevention and management. Moreover, biological control leverages the power of beneficial organisms, including bacteria, parasitic fungi, and predatory insects, to suppress disease-causing pathogens (Hajji-Hedfi et al. 2023a; Rhouma et al. 2024). The integrated plant disease management (IPDM) strategies provide a holistic approach, seamlessly integrating chemical control with cultural practices and biological control, for a comprehensive and sustainable solution to plant disease management (Kumar et al. 2019).

Moreover, IPDM, also known as integrated pest management (IPM) provides a multifaceted approach to plant disease prevention and control and adopt agro-ecological farming, while minimizing the reliance on chemical pesticides (Kogan & Jepson 2007). The IPDM promotes a holistic and long-term strategy for disease control through considering the ecological, biological, and cultural factors that influence disease development. Sustainable agriculture and integrated plant disease management are inseparable partners, as resilient farming systems and the application of sustainable practices can significantly reduce the impact of diseases on crops. The synergetic combination of cultural practices, biological control, and targeted pesticide application allowed farmers to effectively control diseases, minimize crop losses, and promotes sustainable agricultural practices (Agrios 2005; Fisher et al. 2012).

Recent advancements in genomics and molecular diagnostics have revolutionized the identification and characterization of plant pathogens, significantly enhancing disease surveillance and detection capabilities. These methods enable rapid and accurate identification, facilitating the implementation of targeted control measures. Furthermore, ongoing research is actively exploring environmentally friendly and sustainable disease management approaches, including the development of plant-based extracts, bio-pesticides, and biotechnological interventions (Sharma et al. 2020). The current research emphasize the friendly and target-specific products while negative impacts on beneficial organisms and the environment (Grafton-Cardwell et al. 2021).

In essence, this integrated approach offers a comprehensive and enduring solution for combating plant diseases and ultimately promotes long-term environmental health and food security, safeguarding both crop yields and farmers' livelihoods (Hajji-Hedfi et al. 2023a, 2023b, 2023c, 2024a, 2024b; Rhouma et al. 2023a, 2023b, 2024).

Plant diseases: pathogenicity, concerns

Endemic, emerging and reemerging plant diseases affect negatively food access, availability, utilization, and stability and accordingly threat the main pillars of food security (Shkalikov et al. 2010; Savary et al. 2019).

Plant pathogens infect susceptible and healthy plant when environmental conditions are favorable. The infection resulted in plant physiological processes alteration and others functions such as the growth and the structure. The plant subjected to diseases both in the field and in post-harvest showed disease signs that significantly reduce their productivity, quality, and even cause their death. The symptoms of plant diseases include wilting, spotting (necrosis), mold, pustules, rot, hypertrophy and hyperplasia (overgrowth), deformation, mummification, discoloration, and destruction of the affected tissue (Shkalikov et al. 2010; Nazarov et al. 2020; Mwangi et al. 2023).

Plant diseases can be roughly grouped according to the types of causal agents, either infectious or non-infectious. An infectious plant disease is caused by a pathogen such as a fungus, bacteria, virus, and nematode. An infectious agent is capable of multiplying in or upon its host and spreading from one plant to another. Non-infectious plant diseases are caused by non-proper environmental conditions, including extreme temperature, unfavorable moisture/oxygen ratios, toxic substances in the soil or atmosphere, and an excessive or deficient supply of an essential mineral. Non-infectious agents are not transmissible, since are not able to reproduce within a plant host (Nazarov et al. 2020; Smith 2020; Rhouma et al. 2023a).

Various dynamics are assumed to lead the disease emergence and pathogenicity including the interaction amongst various pathogenic bacteria and fungi, interactions between pathogens and plants, interactions among insect-pathogen-plant, in addition to environmental conditions. Plant diseases where more than one pathogen is involved in the infection process are commonly termed as “complex”. This synergetic interaction between plant pathogens increases the complexity and the severity of the disease and must be taken into consideration in the development of more effective control measures (Mwangi et al. 2023).

Fungal pathogenic factors are metabolites produced by phytopathogenic fungi upon plant contact. Their biosynthesis is initiated by physiological and biochemical processes within the fungus, triggered by interactions between fungal and plant surfaces and subsequent signal transduction. These factors, primarily consisting of enzymes such as cell wall-degrading enzymes, toxins, and growth regulators and their analogs, exhibit pathogenic properties toward plants (Félix et al. 2019; Vitorino et al. 2020).

Cell wall-degrading enzymes secreted by phytopathogenic fungi degrade plant cell walls and cuticles, facilitating fungal invasion, colonization, and growth. Molecular biology and proteomics advancements have enabled an increased understanding of the interaction between these enzymes and plants during infection. Pectinase, chitinase, cellulase, and protease are primary cell wall-degrading enzymes (Peng et al. 2021). *Rhizoctonia solani* produces cell wall-degrading enzymes capable of degrading maize radicles, with degradation increasing proportionally to enzyme concentration (Guerriero et al. 2015; Janusz et al. 2017). Cellulases secreted by pathogens soften and decompose plant cell walls. *Fusarium graminearum* secretes cellulase, xylanase, and pectinase during infection, degrading cell wall components and promoting pathogen penetration and expansion. β-galactosidase, a cell wall-degrading enzyme, promotes lactose degradation in cell walls, producing galactose and glucose, and accelerating fruit softening. β-galactosidase is abundant during early fruit softening and degrades cell wall galactosyl bonds, reducing cell wall integrity. Additional enzymes, including hemicellulase, protease, amylase, and phospholipase, degrade hemicellulose, protein, starch, and lipids, contributing to the pathogenic process (Ma et al. 2019). While cell wall-degrading enzymes are crucial for fungal pathogenesis, hormones, toxins, and other factors also contribute to disease development. Conversely, plant defense enzyme systems are activated upon pathogen infection, inducing the production of antifungal substances to inhibit fungal cell wall-degrading enzymes and promote disease resistance. Consequently, plant-pathogen interactions represent a complex biochemical process (Félix et al. 2018, 2019).

Phytopathogenic fungi produce low-molecular-weight secondary metabolites termed toxins, contributing to plant disease development. These toxins induce symptoms including wilting, growth inhibition, chlorosis, necrosis, and leaf spotting (Jajić et al. 2019; Yang et al. 2020). Tenuazonic acid (TeA), identified as the Crofton-weed toxin produced by *Alternaria alternata*, inhibits photosynthetic oxygen release and reduces leaf quantum efficiency. TeA completely inhibits photosystem II electron transfer, targeting the D1 protein. Ascaulitoxin aglycone, a metabolite from *Ascochyta caulina*, exhibits herbicidal activity against *Chenopodium album*. Tentoxin, a cyclic tetrapeptide from *Alternaria alternata*, inhibits chloroplast development without directly affecting chlorophyll synthesis (Pusztahelyi et al. 2015). Cyperin, a phytotoxic metabolite from *Ascochyta cypericola*, *Phoma sorghina*, and *Preussia fleischhakii*, inhibits plant enoyl (acyl carrier protein) reductase, a target site for trichloroarsenic synthesis (Santos et al. 2020). Toxins increase host plant cell membrane permeability, causing electrolyte leakage, membrane damage, and metabolic disruption, leading to physiological dysfunction and death (Huffaker et al. 2011). Toxins damage chloroplast inner membranes, causing basal lamella disintegration and vesicle formation, resulting in severe poisoning or host death (Jajić et al. 2019). Mitochondrial damage, including membrane structure disruption, cristae swelling, vacuolization, and matrix reduction, occurs due to toxin action (Yang et al. 2020). While plant-pathogenic fungal toxin application remains in the laboratory research stage, bioengineering technologies such as cell engineering and tissue culturing are expected to facilitate practical applications (Lyu et al. 2015).

Phytopathogenic fungi manipulate plant hormone levels to suppress host defenses during infection, producing plant growth regulators (Jaroszuk-Scise et al. 2019). *Magnaporthe oryzae* synthesizes auxin indole acetic acid (IAA), potentially inducing plant growth and suppressing defenses (Krause et al. 2015). *M. oryzae*-synthesized cytokinins (CKs) influence rice defense, nutrient distribution, and oxidative stress tolerance, enhancing fungal pathogenicity (Jaroszuk-Scise et al. 2019). Increased gibberellic acid (GA) levels in infected plant cells may activate carbon pool activity, benefiting fungal growth. Abscisic acid (ABA), synthesized by various plant pathogens including *M. oryzae*, promotes fungal growth and appressorium formation (Lievens et al. 2017). Ethylene (ET) effects on fungal pathogenicity vary, with high concentrations promoting growth in some fungi but inhibiting it in others (Ding et al. 2016). Plant-synthesized ET can increase pathogen gene expression and promote infection. Salicylic acid inhibits fungal growth in several species. *M. oryzae* synthesizes jasmonic acid (JA) derivatives, disrupting host JA signaling and weakening defenses. Understanding phytopathogenic fungal hormone synthesis and signaling pathways may identify new drug targets (Jaroszuk-Scise et al. 2019).

Phytopathogenic fungi secrete effector proteins that interact with host plants during infection, influencing plant-pathogen interactions. Effector research has primarily focused on model fungi and those with sequenced genomes (Tan & Oliver 2017). *Botrytis cinerea* secretes an exopolysaccharide that stimulates the host's SA signaling pathway, inhibiting the JA signaling pathway. *Magnaporthe oryzae*'s antibiotic biosynthesis monooxygenase converts JA to 12OH-JA, reducing plant disease resistance (Tilocca et al. 2020). *Verticillium dahliae* effector protein VdSCP41 targets host plant cell nuclear immune regulatory factors, interfering with transcription factor activity and inhibiting immune-related gene induction (Qin et al. 2018). *M. grisea*'s secreted protein slp1 binds to chitin oligosaccharides produced during cell wall degradation, preventing CEBiP recognition and inhibiting the chitin-induced immune response (Tan & Oliver 2017). Effector genes are also known as avirulence genes (Avr), while host plants possess resistance genes (R) (Wang et al. 2018). The interaction between plant-pathogenic fungi and host plants can be understood as the interaction between Avr and R genes (Cobos et al. 2019). Recognition of Avr gene products by R gene products leads to incompatibility and disease resistance, while non-recognition results in compatibility and disease (Yu et al. 2019).

Disease development and transmission: Pathogenesis and saprogenesis

The stage of disease when the pathogen closely associates with living host tissue is known as pathogenesis, which involves three distinct phases. The first phase, known as inoculation, involves the transmission of the pathogen to the infection site or area of plant invasion, which could be the unbroken plant surface, various wounds, or natural apertures such as stomata or lenticels (Rhouma et al. 2023a, b). The second phase is the incubation: the time duration between the pathogen's arrival and the disease symptoms' appearance (Rhouma et al. 2023a, b). The last one is the infection: the development of symptoms associated with the pathogen colonizing and spreading (Rhouma et al. 2023a, b).

One of the most important properties of pathogenic organisms, about their ability to infect, is their virulence. Virulence contains various factors including cell-killing toxins, cell wall-disrupting enzymes, extracellular polysaccharides, and substances that inhibit normal cell growth (Rhouma et al. 2023a, b).

Pathogens are not equally virulent. Some of them do not produce equal amounts of substances (secondary metabolites, effectors, enzymes, etc.) that invade and destroy plant tissues. Nor are all virulence factors activated in any disease. For example, toxins that kill cells are important in necrotic diseases, and enzymes that destroy cell walls are important in soft rot diseases (RoyChowdhury et al. 2022; Rhouma et al. 2023a).

Several pathogens, particularly bacterial and fungal ones, spend part of their life cycle as pathogens and the rest as saprotrophs. Saprophyte are the organisms that are not in vital association with living host tissues, growing in dead host tissues or becoming dormant. During this stage, some fungi produce their sexual fruiting bodies (apple scab caused by *Venturia inaequalis* produces spore-producing perithecia that is ejected with dry leaves). Other fungi produce compact resting bodies, such as the sclerotia of certain root and stem rotting fungi (*Rhizoctonia solani* and *Sclerotinia sclerotiorum*) or the ergot fungus (*Claviceps purpurea*)(Carling 2002). In the absence of a living host, these dormant bodies, which are resistant to extremes of temperature and moisture, allow the pathogen to survive in soil and plant debris for months or years (Carling 2002; Rhouma et al. 2023a, b).

Environmental factors influencing disease development

Environmental factors include weather conditions, especially temperature and humidity that should be favorable for the reproduction; dissemination and infection of the pathogen; the introduction of a new and more vulnerable host; the development of a very virulent race of the pathogen; and changes in cultural practices that create a more favorable milieu for the pathogen. Important environmental factors comprise temperature, relative humidity, soil moisture, fertility, and pH, which can influence the development of plant diseases and determine whether they become epiphytic (Rhouma et al. 2019).

The development of infectious diseases is not possible if any of the three basic conditions are absent: (1) a virulent pathogen, (2) a susceptible host, and (3) the right environment, with the proper amount of water, as well as optimal air and soil temperatures. Effective disease control measures aim to break this pathogen-host-environment triangle (Rhouma et al. 2023c).

The development and spread of plant diseases are heavily influenced by a variety of environmental factors (Van der Heyden et al. 2020). Temperature plays a crucial role in determining the growth rate and survival of both pathogens and host plants (Rodriguez-Algaba et al. 2020). High temperatures can favor the development of some diseases, while low temperatures may inhibit pathogen activity. Humidity is another important factor, as many pathogens require high humidity levels for their growth and sporulation (González-Domínguez et al. 2020). Precipitation can also influence disease development by providing favorable conditions for pathogen dispersal and infection. Wind can aid in the spread of plant pathogens, particularly those that produce airborne spores (Rodriguez-Algaba et al. 2020). Soil conditions, including pH, nutrient availability, and water content, can also affect the susceptibility of plants to diseases (Rhouma et al. 2019).

Understanding the complex interactions between environmental factors and plant diseases is essential for developing effective disease management strategies (González-Domínguez et al. 2020). By monitoring environmental conditions and implementing appropriate control measures, it is possible to minimize the impact of plant diseases on agricultural production (Lu et al. 2020).

Classification of plant diseases

These diseases combine a wide range of infections caused by a diversity of pathogens. They manifest in different forms affecting different plant parts and tissues, such as leaf spots, wilting, rotting, cankers, and blights. The impact of plant diseases on crop productivity and quality is immense, resulting in economic losses and reduced yields (Agrios 2005).

Physiological symptoms are commonly used to classify plant diseases. However, many diseases have virtually identical effects but are caused by different microorganisms or pathogens, requiring completely different management practices (AL-Taie et al. 2024). Classification based on symptoms is also inappropriate because a single pathogen can cause a several distinct symptoms, even on the same part of the plant, and these symptoms often overlap. The classification may be built on the plant species involved and then, host indexing is a valuable diagnostic tool. Checking the index for the given host often helps to identify the pathogen when a new disease is found on a known host. Diseases can also be classified based on the major function or process that is compromised. The causal agent, such as a non-infectious or infectious agent is the most appropriate and commonly used method of classifying plant diseases. Non-infectious agents include generally unfavorable environmental conditions (temperature, water, pH, mineral nutrients, and light), chemical pollutants, and accidental physical injuries whereas infectious agents are fungi, bacteria, viruses, nematodes, and parasitic plants (Smith2020; Rhouma et al. 2019).

Fungal diseases

Fungi cause the vast majority (2/3) of infectious plant diseases, and it seems that all economically important plants are confronted with one or more fungal pathogens. The general and common characteristics of these pathogens is a plant-like vegetative body consisting of microscopically branched, filamentous threads of varying lengths called hyphae, some of which extend in the air while others invade the support on which they are growing (Fontem et al. 1996).

The hyphae are organized in a network called mycelium which mass characterizes the cottony appearance of fungal growth. Fungi use both asexual and sexual methods to reproduce and produce very large numbers of different types of spores. These spores or vegetative organs may be transported and dispersed in many ways (air currents, splash and rainwater, soil and dust, insects and birds, and debris of infected plants). In nature, climatic conditions, particularly temperature and humidity, determine the survival of vegetative cells of plant pathogenic fungi. The vegetative cells can tolerate temperatures ranging from -5°C to 45 °C, but the spores of the fungus are much more resistant. However, spore germination is facilitated by moderate temperature and high moisture (Dhingra et al. 1978; Burgess et al. 2008).

Fungal attacks can cause typical symptoms of localized or widespread necrosis on the plant or plant tissue. It can also prevent normal development (hypotrophy) or cause excessive aberrant growth (hypertrophy or hyperplasia) in part or the whole plant. Necrosis symptoms include leaf spot, blight, and scab, rot, dampening off, anthracnose, leaf curling, canker, and dieback (deep lesions). For example on affected Cassava plants, the stems and branches show cankers at the base of the leaf petiole, the tips are desiccated and the petiole is weaken. The leaves then wither, dry out and fall, causing defoliation and dieback, or even the total death of the shoot. In most cases, the disease is triggered at the start of the rainy season and then increases with the rains (Banyal et al. 2008; Rhouma et al. 2024).

On roots, symptoms are associated with hyperplastic growth and include club root needle casting, galling, and warting as well as root rooting. In 40-90% of cases of root rot; symptoms also appear on the leaves: they turn brown and wilt. The plant loses a lot of water and may die. Root colonization is marked by mycelial development on the bark or between the bark and the wood and root; degradation is due to enzymatic or toxic activity of the pathogen (Biggs 1989, 1995; Byrne et al. 1997; Marquez et al. 2021).

On cassava, the disease appears during the rainy season. Cassava root rot destroys both feeder roots and tuberous roots. The tuberous roots may swell unusually and roots appear in a light brown color that is visible when the roots split in the soil, or when they are cut. As the roots rot, they can give off a foul odor (Table 1)

Bacterial diseases

Bacteria are unicellular microorganisms with a cell wall but no organelles and no nuclear membrane. Multitudes of bacterial species are present in natural plant ecosystems. Some survive as detritivores that decompose organic matter in the environment. Others are harmful to animals and plants. Air, water, insects, animals, soil, humans, and infected seeds or plants could spread these microorganisms (Jiménez-Jiménez et al. 2022). Most bacteria need an aperture (wound, stoma, lenticels, etc.) to enter the host's tissues and require suitable conditions like nutrients, humidity, and temperature to develop and establish. Phytopathogenic bacteria develop between the plant cells by absorbing the cells' nutrients and then colonizing the host body or multiply in the plant's vascular tissue. They produce and release enzymes, growth regulators, or toxins that affect health and normal plant development (Cameron 1970).

The symptoms of plant bacterial infections are similar to those of fungi. They can range from excessive growth, leaf necrotic spot, blight, scab, vascular wilting, and canker to rot and tumors of roots, storage organs, and fruits. One genus of bacteria can present different sorts of damage according to the species, the host plant, and the cultivation or storage conditions (Table 2) (Hatting et al. 1989).

Table 1 Some important plant pathogenic fungi and respective damages (Dhingra et al. 1978 ; Biggs 1989, 1995; Fontem et al. 1996; Byrne et al. 1997; Banyal et al. 2008; Marquez et al. 2021; Hajji-Hedfi et al. 2023a,2023b,2023c, 2024a, 2024b; Rhouma et al. 2023a, 2023b, 2024)

Fungi	Plant	Damages
Phytophthora capsici	*Capsicum* spp. (peppers)	Root rot, stem blight, fruit rot
Puccinia graminis	Wheat	Leaf rust, stem rust
Fusarium oxysporum	Many plant species	Wilt disease
Botrytis cinerea	Various fruits and vegetables	Grey mold rot (watery soft rot on fruits, stems, and flowers)
Alternaria solani	Many plant species	Early blight (dark brown spots on leaves, stems, and fruit, leaf spots, defoliation)
Pythium spp.	Many plant species	Damping-off (seedling death), root rot
Erysiphe graminis	Cereals	Powdery mildew
Mycosphaerella pinodes	Peas	Ascochyta blight
Rhizoctonia solani	Many plant species	Damping-off, stem canker, root rot, black scurf, stolon canker
Colletotrichum gloeosporioides	Various fruits and vegetables	Anthracnose (fruit rot, leaf spots, cankers)
Phytophthora infestans	Many plant species	Late blight (defoliation, tuber rot, foliage and fruit lesions, rapid plant death)
Fusarium spp. (e.g., *F. solani*, *F. oxysporum)*	Many plant species	Fusarium wilt (wilt, dry rot, vascular discoloration)
Verticillium dahliae	Many plant species	Verticillium wilt (stunting, yellowing, defoliation)
Sclerotinia sclerotiorum	Many plant species	White mold (white fluffy mold on stems and fruits, fruit rot)
Spongospora subterranean	Potato	Powdery scab (deformed tubers)
Colletotrichum coccodes	Potato	Black dot (tuber blemishes)
Helminthosporium solani	Potato	Silver scurf (superficial tuber blemishes)
Synchytrium endobioticum	Potato	Wart disease (wart-like growths on tubers)
Spilocaeaoleaginea	Olive	Peacock spot (leaf spots, defoliation)
Phoma sp.	Olive	Olive leaf spot (leaf spots, defoliation)
Botryosphaeria dothidea	Olive	Olive dieback (branch dieback, cankers)
Rosellinia necatrix	Olive	Black root rot (root rot, decline)
Fusarium oxysporum f. sp. *eleagni*	Olive	Fusarium wilt (vascular wilt, stunting)
Armillaria mellea	Olive	Armillaria root rot (root rot, decline)
Phaeoacremonium aleophilum	Olive	Olive leaf scorch (leaf scorch, defoliation)
Phomopsis elaeagnus	Olive	Olive twig dieback (dieback of twigs and branches)
Cladosporium fulvum	Tomato	Leaf mold (brown spots on leaves and fruit, defoliation)
Fusarium oxysporum f. sp. lycopersici	Tomato	Fusarium wilt (vascular wilt, yellowing, plant death)
Colletotrichum coccodes	Tomato	Tomato anthracnose (fruit rot with sunken lesions)
Didymella lycopersici	Tomato	Stem canker (cankers on stems, fruit rot)
Didymella bryoniae	Cucurbits	Gummy stem blight (stem lesions, wilting)
Monosporascus cannonballus	Cucurbits	Monosporascus root rot and vine decline (root rot, vine decline, fruit yield reduction)

Table 2 Some bacterial diseases and their damages (Cameron 1970; Hatting et al. 1989; Jiménez-Jiménez et al. 2022)

Division	Genera	Causal agent	Damages
Gram$^-$	*Erwinia*	*E. amylovora* *E. chrysanthemi,* *E. carotovora*	Fire blight of pear and apple, Stewart's wilt in corn Soft rot of fleshy vegetables.
	Acidovorax	*A. avenae*	Leaf spots in corn, orchids and watermelon.
	Agrobacterium	*A. tumefaciens* *A. rhizogenes* *A. vitis*	Canker of stems or roots of many genera of woody plants becoming tumoured, wrinkled, and turning brown to black
	Pseudomonas	*P. asplenii,* *P. syringae,* *P. Marginalis* *P. solanacearum*	Leaf spots, blights, vascular wilts, soft rots, cankers, and galls.
	Xanthomonas	*X. campestris* X. arboricola	Leaf spots, fruit spots, blights of annual and perennial plants, vascular wilts and citrus canker.
	Xylella	*X. fastidiosa*	Xylem-inhabiting bacteria, leaf scorch and dieback disease on trees and vines.
Gram$^+$	*Arthrobacter*	*A. oryzae* *A. oxydans* *A. nicotianae*	Bacterial blight of holly Douglas-fir bacterial gall.
	Clavibacter	*C. michiganensis* *C. toxicus*	Bacterial wilts in alfalfa, potato, eggplant and tomato.
	Streptomyces	*S. scabies*	Common potato scab Pod wart of peanut

Nematodes' diseases

Plant parasitic nematodes are extremely damaging to a wide range of plant hosts. They may attack and establish on seeds, roots, tubers, foliage, stems, as well as flowers (Hajji-Hedfi et al. 2023c). Plant parasitic nematodes are characterized by piercing stylets, used in the perforation of plant tissues and for nutrition which differentiate them from other groups of nematodes. The nematodes perforate the cell walls and inject secretions from their salivary glands, which are rich in enzymes that transform the architecture and the density of cell contents. A part of this content is then sucked up by the nematode using their style. The nematode feeding process diminishes the natural defenses; decreases the vigor and the production of plants and offers entrance wounds for other soil phytopathogens (Hajji-Hedfi et al. 2023b).

In most cases, the symptoms of nematode infestation are confused with damage caused by abiotic stresses, and show up as poorly developed, stunted plants, yellowing foliage, and slow dieback. In the field, these troubles are concentrated in areas or sites of infestation. The underground organs present some types of damage specific to certain genera of nematodes such as galls and egg masses for *Meloidogyne*, lesions and rot for *Pratylenchus* and *Ditylenchus*, cracks and cysts for *Globodera* and *Heterodera*. The weather (temperature, humidity, moist, light), and soil characteristics (soil type, texture, structure, organic matter, water, and nutrients) affect nematode populations, rates, and plant damage (Table 3) (Hajji-Hedfi et al. 2023b).

Viral diseases

Viruses are very small plant infectious agents (250-400 nm). They are obligate parasites of plant living cells. They are responsible for important damages to many crops like cereals (oat, rice, maize, etc.), vegetables (potato, tomato, pepper, watermelon, etc.), fruits trees (peach, orange, palm, etc.) as well as fodder and industrial plants (sugar beet, sugar cane, rape, sesame, etc.). Generally, virus disease is expressed by stunting and malformation of parts or of the entire plant associated with yellowing commonly called mosaic, and necrosis of vegetation. As a consequence, a reduction and depreciation of production are always recorded, and in some cases, plants die back (Rodríguez-Verástegui et al. 2022). However, one or more viruses may infect plants without expressing any symptoms due to plant tolerance or external conditions like temperature. These plants are latent sources of contagion and dissemination of the disease agent. Insects, nematodes, seeds, pollen, and even simple contact between plants may also spread viruses. Plant visual diagnosis of viral diseases needs to be confirmed by laboratory analysis (Table 4) (Shrestha et al. 2018).

Table 3 Some important plant pathogenic nematodes and respective damages (Hajji-Hedfi et al. 2023b,c)

Nematode	Plant	Damages
Globodera rostochinensis	Potato crops	Scabs, crakes, vigor and production decrease
Ditylenchus dipsaci	oat, rye, rice, onion, sugar beet, bulb plants	Bloat, swollen, soft rot, production depreciation
Meloidogyne spp.	tomato, pepper, potato, carrot, soybean, grass plants, olive trees, stone fruits trees, ornamental plants …	Galls, root distortion, vigor decrease and production devaluation
Pratylenchus spp.	Vegetables, olive trees, ornamental plants	Root lesions, root blackening and rots, production decrease
*Heterodera avena*e	Cereals	Plant wilting sickly, stunted plants, production diminution
Xiphinema sp., *Longidorus* sp.	Vine, ornamental plants ,	Virus transmission, stubby plants, products degradation
Aphelenchoides sp.	Rice, strawberry, celery, vegetables	Leaves blisters, stem distortion, plant wilting

Table 4 Some of virus's diseases and damages (Shrestha et al. 2018)

Virus	Plant	Damages
Tobacco and tomato mosaic virus	Tobacco, tomato; eggplant; bitter melon; mustard; watermelon; bean; cabbage.	Leaf Mosaic; mottling; distortion; defoliation.
Pepper mottle virus	Pepper and chilis	A mottle or mild mosaic
Torrado virus (TV)	Pepper, tomato, eggplant, and weeds (*Amaranthus*, *Chenopodium*, Atriplex and Malva)	necrotic spots; holes in the leaflets; defoliation;
Yellow leaf Curl Virus (YLCV)	Bean, cucurbits, Pepper, weeds	Intervene yellowing Leaves thickened and twisted down wards Reduced production quality.
Iris Yellow Spotted Virus (IYSV)	Garlic, Onion, leek	Diamond shaped or Eyelike spots on leaves, general yellowing.
Spotted Wilt Virus (SWV)	Tomato, Potato, Pepper, Eggplant; Peas; Basil, Lettuce, Celery	Ring spots, mottling, and yellowing blemishes on leaves.
Potato and cucumber mosaic virus (PMV)	Potato, tomato, Capsicum, Celery.	plants are stunted Chlorosis and mottle of leaves
Potato Leaf Roll Virus (PLV)	Potato	Underdeveloped plants; Margin lower leaves develop thick texture, roll up wards and fall prematurely.
Celery Mosaic Virus (CMV)	Parsley, celery, Coriander	Stunted plants, pronounced yellowing and curling on the top leaves

Plant diseases management

Effective disease management requires a full understanding of the pathogen, the disease process, host-pathogen, and environmental factors interactions, as well as the cost. Control starts with the selection of the best available variety, seed, or planting stock and extends through the whole growth cycle. Disease control extends to the transport, storage, and marketing of harvested crops. There are relatively few diseases that could be controlled by a single method; the majority require a combination of biological, cultural, and chemical methods in a global approach to control as many different pests as possible on a set crop. Associated control measures target pathogenic agents and include principles of restriction or prevention, elimination, selection, resistance, and treatment (Hajji-Hedfi et al. 2023a, 2023b, 2023c, 2024a, 2024b; Rhouma et al. 2023a, 2023b, 2024).

The cultural practices and biological and chemical control tactics were considered the major component of IPDM; due to its definition as "a sustainable approach to managing diseases by combining biological, cultural, physical and chemical tools in a way that minimizes economic, health and environmental risks". Each disease management approach acts dependently in an IPDM program (Smith 2020).

Cultural Practices

Cultural practices lie at the heart of integrated disease management, aiming to create environments that hinder disease development. In intensive farming systems, plant diseases are severe; management can be done by integrating different methods including cultural practices. Cultural practices are human activities that reduce disease incidence through the cultural manipulation of plants. The sanitation measures, like removing infected plant debris, prevent disease spread and disrupt disease cycles by minimizing pathogen build-up in the soil (Rhouma et al. 2023a). They are the oldest and most fundamental approaches used to prevent plant diseases and they might be used even before or after crop planting. They are classified as pre-planting and post-planting cultural methods. Some practices like flooding, removal of weeds, deep tillage, and soil solarization, disease-resistant plant varieties can be used before planting (Smith & Oyarzún 1997; Bock et al. 2009; Pandey & Yang 2016). Otherwise, irrigation, manuring, adjusting sowing/harvesting time, and the use of mineral fertilizers could be used after planting (Howard 1996; Shubha et al. 2021). Knowledge of the interaction between plant host, pathogen, and environment is the crucial key to the efficient application of any cultural practices.

This integral component of disease control programs for most crops, with the first goal to be used for the management of soil-borne pathogens or as the farming system, is assorted into three categories: 1) Practices for regular agricultural purposes that can also be used for disease control, e.g. irrigation. 2) Practices used solely or mainly for pest control, e.g. sanitation. 3) Practices that can be used for agricultural purposes and pest control, e.g. crop rotation (Katan 2004).

Biological control

Beyond cultural practices, biological control is another critical pillar of integrated disease management. It harnesses the power of natural enemies, such as beneficial insects and microorganisms, to suppress disease-causing organisms (Whipps 2001; Jaronski 2010).

Biological control is most usually defined as a method of plant disease management by inhibiting directly or indirectly plant pathogens, improving plant immunity, and/or modifying the environment through the effects of beneficial microorganisms, compounds, or healthy cropping systems. The beneficial microorganisms are termed the biological control agent (BCA) (Jensen et al. 2016; Tronsmo et al. 2020). A great number of biocontrol microbes have shown an outstanding growth-promoting effect and disease control over the last years (Jaiswal et al. 2022; Ghazi Mohammed et al. 2024).

Biological control agents have different mechanisms to manage plant disease. They can parasitize directly the pathogens, produce antibiotics, or compete for niches and nutrients (Ghosh et al. 2018; Hajji-Hedfi et al. 2023c). Some beneficial microorganisms induce or prime plant immunity systems and reduce indirectly the development of plant pathogens (Conrath et al. 2015). Some fungi; such as the *Trichoderma* genus able to induce host plant immunity and enhance host resistance through some secondary metabolites that can be involved in signal transduction and catalytic activities (He et al. 2021; Hajji-Hedfi et al. 2023a).

Microbial-based bio-pesticides can be used to mitigate plant diseases as well as to improve plant growth. The modern agriculture require improving plant health and productivity. Microbial-based biostimulants offer an innovative biotechnological solution for sustainable agriculture; in particular, the probiotechnology that is the use of beneficial microorganisms or probiotics, in biotechnological applications (Bernauer and Meins, 2003). Microbial inoculants typically consist of bacteria, fungi, and arbuscular mycorrhizal fungi (AMF). Many microorganisms have individually beneficial effects on plant health and yield, which can be further enhanced when they act together in consortia. Microbial consortia involve compatible microorganisms that have additive advantageous effects on soil and crop quality (Dheeman et al. 2023; Ahmad & Pandey 2024).Biological control management is considered one of the most promising effective, eco-friendly approaches for sustainable agriculture. Furthermore, this approach guarantees the most economical and long-term effective strategies for managing plant diseases, reducing crop loss, and safeguarding food. This method provides numerous benefits when compared with other approaches to chemical treatment; as the BCAs have specific target pathogens and have not many ecological issues (He et al. 2021; Jaiswal et al. 2022; Omidvari et al. 2023).

Chemical Applications

The chemical approach is the management of plant pathogens using pesticides. They can be used in different ways depending on the controlled pathogen and the circumstances (Rhouma et al. 2023b). The chemical control of plant diseases is classified into three categories: seed treatments, soil treatments, and protective sprays and dusts (Zheng & Xu 2023).

For example, more than 150 chemical compounds using different mechanisms of action are registered as fungicides. Otherwise, many other products have been taken off the market, banned or have failed to pass re-registration and this due to the strit regulation in handling chemical pesticides (Nazarov et al. 2020).

In an IPDM, chemical treatment needs to be applied within the economic benefit from proper timing of reduced pesticide doses, which gives substantial increases in net yield and cost-effectiveness (Klink et al. 2021). Another strategy is the proper choice of pesticide; its dose and application time are important in achieving economic efficacy. In addition, pesticides are selected and applied in a way that minimizes their possible harm to people, non-target organisms, and the environment. Therefore, pesticides are used only when needed and in combination with other approaches for more effective, long-term control (Jaiswal et al. 2022).

Integrated plant disease management (IPDM) principles

IPDM programs employ three primary disease control strategies. First, to prevent contamination, pathogen avoidance is achieved by maintaining healthy soil, materials, and plants through disinfection and quarantine (Rhouma et al. 2023a, b). Secondly, disease avoidance is accomplished by strategic planting timing and location to minimize pathogen exposure or susceptible plant stages coinciding with favorable pathogen conditions (Dudek & Rosa 2023). This involves considerations such as geographical area, field selection, sowing time, seed and planting material choice, variety selection, and agronomic practices (Kumar et al. 2019; He et al. 2021). Thirdly, upon pathogen establishment and disease onset, purging or defending measures are implemented, including cultural practices like crop rotation and diseased plant removal, utilization of resistant or tolerant cultivars, and chemical treatments (Rhouma et al. 2023c; AL-Taie et al. 2024). Subsequently, protection measures are employed to prevent re-contamination by managing the environment, implementing specific cultural practices, optimizing handling methods, controlling disease vectors, and applying pesticides (Hyder et al. 2022). Finally, a protective barrier is created between plant surfaces and inocula to safeguard against rapidly spreading pathogens through chemical sprays, dusts, environmental modification, and host nutrition adjustments (Jaiswal et al. 2022).

IPDM strategies

As it is impossible to completely eradicate disease agents especially when they are gathered on an established crop, integrated disease management is about the combination of multiple practices to reduce the disease's damages to an accepted or tolerated rate. Such practices take into consideration the environmental records, pathogen biology as well as the available controlling technologies or tools. Control methods include biological mechanisms, habitation handling, cultural practices changing, and resistant varieties use. Pest management tools can be applied separately but in this approach of IPDM, they need to be complementary and positively interact between them to reduce the impact of the disease on the ecosystem and the people's lives (Khoury et al. 2010). Some management practices are not directly applied on to crops, but their goal is to reduce the inoculums in the soil, like organic amendments, fumigants, herbicides, solarization, and tillage will figure in an IPDM program as they participate in reducing the disease incidence (Lodha et al. 2020).

Integrated management of viruses diseases

After infection by viruses, it is too late to reestablish plant health. However, the combination of several management methods could fruitfully avoid contamination. One important aspect of managing viruses' diseases is to correctly identify the virus that is causing the disease and then apply a suitable strategy for effective management (Rodríguez-Verástegui et al. 2022).

It is based first on quarantine and growing crops in healthy regions, second on eradicating spreading agents like infected plants, weeds, nematodes, and insects' vectors of viruses to limit contamination zones, and finally on using barriers to prevent infection like resistant varieties.

Changes in the populations of vectors play a significant role in the emergence of viral epidemics in plant crops (Anderson et al. 2004). These populations are directly related to surrounding climate parameters, the cropping system, and the availability of alternative virus hosts. It is then essential to closely observe and monitor each cropping system for the appearance of new plant disease outbreaks (Shrestha et al. 2018).

Integrated management of bacterial diseases

Usually, it is quite challenging to manage diseases caused by bacteria. The reason is partially due to the quickness with which bacteria can invade the plant tissue through natural openings or wounds. An immediate introduction also allows them to evade the harmful impacts of chemical protections. The use of pathogen-free seeds grown in unaffected regions helps decrease losses caused by bacterial infections (Krasnow & Norman 2022; Costa et al. 2023). Disinfection of seeds with hot water (≃50°C) is one of the important preventive measures used to control bacterial infections treating seeds at about hot water is active for cucurbits, cruciferous, and *solanaceous* plants. Crop rotation with non-host plants reduces losses on alfalfa due to wilt, on beans due to blight, on canola due to black rot, and on tomatoes due to bacterial spot and canker (Soto-Caro et al. 2023).

Suppression of infected plants is convenient in combating canker on citrus, angular spots on cotton's leaves, leaf blight, and crown gall bacterial diseases. Resistant varieties were developed to reduce losses caused by bacterial wilting on alfalfa, tobacco corn, and soybean (Shumilak et al. 2023).

All these issues without forgetting the chemical pesticide sprays that help manage some bacterial diseases, like corn and cucurbit wilting as well as celery and beans blight (Persley et al. 2010).

Integrated management of nematodes diseases

Using certified, nematode-free nursery stock, cultivating resistant kinds and species, rotating non-host plants, and applying soil fumigation (nematicides) as pre- or post-planting treatments are some common nematode control strategies. In small spaces like greenhouses and ground beds, soil is treated with hot steam. Most nematodes and nematode eggs can be destroyed by exposing them to hot moisture (≃50°C) for 30 min or shorter times at higher temperatures. Some international quarantine programs forbid transporting the possible carriers of nematodes like infected soil, plants, seeds, plant parts, and equipment (Pulavarty et al. 2021).

The use of heavy organic mulches or cover crops, proper fertilizer application, clean cultivation, and plow-out root systems of susceptible plants after harvesting are all cultural practices that encourage vigorous plant growth. For several plant-infecting nematodes, many plants like asparagus, marigolds, and *Crotalaria* species are used as poisonous or repulsive organic amendments (Shumilak et al. 2023).

Integrated management of fungi diseases

Numerous techniques are available to control fungal infections because the hundreds of different fungal species can infect a wide range of plants, and because each fungal species possesses unique properties (Grove & Biggs 2006; Chen et Liu 2017).

The use of healthy seeds, the removal of any vegetation that can transmit pathogenic fungi, crop rotation, the selection of appropriate fertilization and use of resistant varieties (Zhou & Everts 2016; Shoaib et al. 2022), and the application of chemical fungicides and biological management agents are the main methods of control.

Effective biological microorganisms commonly used in controlling pathogenic fungi are *Bacillus subtilis, Pseudomonas fluorescens*, *Trichoderma viride*, *T. harzianum* and *Penicillium* spp. against *Fusarium oxysporum* and *Macrophomina phaseolina* (Ashwini et al. 2013; Zhao & Zhang 2018; Hyder et al. 2022), *Streptomyces* sp. against *Rhizoctonia* sp. (Adhilakshmi et al. 2014).

Minuto et al. 2007 reported that the management of *F. oxysporum* on chrysanthemum by combining physical methods (pH adjustment and disinfection) and bio-inoculation by microbial consortium including *Streptomyces griseoviridis* and *Trichoderma* spp. was the most effective than each method applied individually (Omidvari et al. 2023).

IPDM opportunities and challenges

IPDM implementation in contemporary agricultural systems offers multiple advantages for plant health, ecosystem equilibrium, and human well-being (Zhao & Zhang 2018; Sharma et al. 2020). A core principle of IPDM is minimizing synthetic pesticide reliance, thereby reducing environmental contamination, human health hazards, and ecological disruption (Ghosh et al. 2018). Recent advancements in biotechnology and genetic engineering facilitate the development of disease-resistant crop cultivars, which can enhance the efficacy and sustainability of IPDM strategies (Shoaib et al. 2022; Dudek & Rosa 2023). The integration of modern plant breeding techniques and the utilization of resistant crop varieties can diminish the necessity for chemical control measures and promote long-term disease management sustainability (Grafton-Cardwell et al. 2021; Zheng et al. 2023).

Technological advancements in agriculture, including drones, biosensors, and precision agriculture, offer enhanced opportunities for IPDM implementation by improving disease detection, monitoring, and management efficiency and sustainability (Grafton-Cardwell et al. 2021; Costa et al. 2023). IPDM promotes eco-friendly practices that contribute to ecosystem health, biodiversity preservation, and natural resource conservation (Sharma et al. 2020; Zheng et al. 2023). The integration of diverse strategies enables sustainable and long-term disease management. Biological control agent utilization within IPDM preserves beneficial microorganisms and overall ecosystem health (Lodha & Mawar 2020). This approach also offers economic advantages through the incorporation of cultural practices and reduced synthetic pesticide application (Ghosh et al. 2018; Grafton-Cardwell et al. 2021).

Successful IPDM implementation necessitates adequate knowledge and expertise, especially among farmers, to accurately apply appropriate management techniques and timing (Chen & Liu 2017). Expanding IPDM practices requires increased awareness through training and outreach initiatives focused on disease management and IPDM benefits (Zhao & Zhang 2018; Costa et al. 2023). IPDM strategies are context-specific and may not be universally applicable across diverse crop, soil, climatic, and disease incidence conditions (Kumar et al. 2019; Dudek & Rosa 2023).

IPDM application and implementation are hindered by challenges related to the integration and coordination of diverse control tactics due to requirements for specific infrastructure, application procedures, and timing (Zhou & Everts 2016; Zhao & Zhang 2018). Effective IPDM integration necessitates regular crop monitoring to determine optimal control measures and application timing (Krasnow et al. 2022). Collaboration among researchers, farmers, policymakers, and extension services is crucial for successful IPDM implementation (Shumilak et al. 2023; Zheng et al. 2023).

Conclusion

Integrated disease management offers a promising approach towards sustainable agriculture by effectively controlling diseases and limiting negative environmental impacts. By combining multiple strategies such as crop rotation, biological control, cultural practices, and judicious use of chemicals, it is possible to achieve sustainable disease control while preserving ecosystem health and ensuring long-term agricultural productivity. This holistic approach highlights the importance of considering the interplay between disease management, crop health, and environmental sustainability for a long-lasting and sustainable agricultural system.

Author contributions

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Conflicts of interest

The authors have no conflict of interest

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