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Etiology, Epidemiology and Management of Diseases: Warfare Between the Pathogen and the Pathologist

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ABSTRACT

Perhaps, pathogens are the main biotic factor that cause diseases of plants reducing yield considerably. Man in its interest and effort tries to defend/protect these plants from the harassment by these pathogens. This review tries to look at the pathogen as a causal agent of diseases, disease development and the pathologist as management strategist employing various options to bring the pathogen under control. This initiative to unravel the causes of disease, disease development and management is seen as a "warfare" between the pathogen and the pathologist as each of them is seen to be smarter in its approach. Different strategies from both ends were examined and mechanisms by which each of them uses to outwit the other in this warfare are discussed. There is no doubt, the pathogen is far ahead and the most intelligent. It always tries to be a step ahead and seems to be dictating the pace with resultant nightmares/sleepless nights to the pathologist. The pathogen also tries to set the questions for the responses from the pathologist. Nevertheless, the pathologist has never relented in its effort to always find an antidote/solution to the swiftly and slippery nature of the pathogen. In nature's own wisdom, perhaps it would be impossible for the pathologist to find a lasting antidote/solution, as this might appear to bring plant pathology as a profession to an end. The fight for supremacy therefore continues unabated.

Keywords: pathogen, pathologist, warfare, different strategies.

INTRODUCTION

Since creation, living things depended on each other for survival. Man, animals, plants and microorganisms depended on each other for food and nutrition. Man, a superior living thing with particular interest in all others tries to protect each of these living things for maximum benefits. Particularly, man depends on plant for all the nutrients needs, be it carbohydrates, protein, fiber, fat and oils, vitamins, minerals etc. Man, also depends on plants for economic and social benefits. For instance, what would have been the faith of national economies like Ghana if it does not protect its cocoa industry against the Black pod disease? With a common saying that "Ghana is Cocoa and Cocoa is Ghana" (OPEC FUND 2022). This has led to man's interest to protect these plants against other competitors such as animal and microorganisms. Microorganisms have been at the forefront in competition against human beings for maximum benefit from the plant. One particular instance is fighting the microorganisms from deriving its nutrient from the plants. In the quest of the microorganisms deriving its nutrient from the plant, not only leaves the plant with pathological effects but also reduce/minimize the yield that otherwise will have served as food for the ever-growing human population (UN report 2019).

It is in view of this that man has always been at the war front with the pathogen doing everything possible to free the plant from these microorganisms as pathogens from causing “harm” to the plant. Pathogens have caused indirectly devastating effect to human race since time in memorial, recalls can be made to the 1846 “Irish famine” that caused death of about half a million people and at the same time the migrating of about same number to United State of America in search of food for survival (Agrios 2005). History tells us that the pathogen has always been a step ahead of man in this warfare. It is the pathogen in its quest for survival, initiates the process of deriving nutrient from the plant. The pathogen finds the plant as a suitable partner/host and therefore initiates close association with it but this association with the help of the environment always becomes detrimental in its effect to the host plant. After exhausting the nutrients from the plant, the plant is denied survival that leads to the decrease in potential yield of the plant or eventually die. Man realizing its dependency of the plant under threat from the pathogen, therefore starts devising means for a fight against the pathogen.

This warfare has lingered on for over a century with each party trying to outwit the other. The question is therefore not about who wins this fight but the various ways the pathogen initiates these diseases, how the diseases develop and the effort man/pathologist makes to manage the disease to bring the effort of the pathogen under control. This review gives insight into the nature of the fight and the strategy each try to employ to outdo the other. The review therefore tries to look at the various mechanisms/strategies use by both the pathogen and the pathologist and the various roles played or contributions made by pathologists to grant the plant the maximum freedom to produce to its maximum capability, so that maximum yield can be derived from the plant to save the ever-growing population to end hunger and malnutrition (SDG goal 2).

HISTORICAL ANTECEDENT OF PLANT DISEASES

It is a common knowledge of the negative effects of plant diseases on food security worldwide which has been acknowledged in time past. Early evidence of plant diseases dated back in the Old Testament of Holy book, the Bible and other early reports by Indians, Sumerians and the Romans made references to plant diseases dated back to 2000 BC with their devastated effect especially causing different levels of famine and other economic loses (Norrie 2016). In fact, early documentation of plant disease at that time was basically descriptive and current concept of diseases and pathogens were non-existence where the causes of those diseases that affected plant appeared superstitious. Evidence of this was the festival of the Romans that was celebrated to pacify and sacrifice of red dogs to appease the gods, because it was believed at the time that rust disease that effected farmers cereals were as a result of dissatisfaction of the gods. One of such festivals was Robigalia and the god was Robigus (Secoy & Smith 1978) and appeasing this god was seen as a method of managing the disease. This era marked the beginning of plant disease control, an important aspect of plant pathology.

Whetzel (1918) in his ‘outline of the history of plant pathology” divided the period of plant pathology into different era; Premodern era (expanding from the 17th to the middle of the 19 century and the Modern era (from the middle of the 19th century to date). During the period of the pre-Morden era, the description of plant diseases became more detailed, systematic and accurate in the time of Johann Batista Zallingger (1731-1785) which became known as the Zallingerian period and constituted the first part of the pre-modern era, then in the later portion of the pre-modern era constituted the "Ungerian period", named after Franz Unger (1800-1870). Franz initiated the process of identifying disease pathogens and their description. The initial perception was that these organisms were not thought to actually cause the diseases but were thought to have been originated from the plant itself rather than from external sources. At this era, the descriptions were not done by Plant Pathologist but rather by Plant Physiologist since the effects on the plant were as a result of disruption of the plant physiological processes rather than the pathogen effect and also due to non-existence of such specialists at the time. The pathogens were thought to have originated through the process of autogenesis, origination of life from non-living things. Despite these assumptions, pathogens were worthy of given names and classification. This initiated the thought and rise to the Modern era with the evolution of the Gem Theory.

Though many scientists in the Ungerian period, believed in the autogenesis, many others were adamant of this believe. One such person was Henry-Loius DuHammel du Moncecau (1728) who gave accurate description of a disease and the pathogen who caused the disease, he demonstrated the pathogen's capacity to survive and propagate independently of the *Saffron crocus* plant. He consequently reported the diseases to be caused by a parasitic fungus, *Helicobasidium purpureum* and concluded that the disease was infectious. Another prominent entomologist, Johan Christian Fabricius of Danish origin, published his ideas about how plants become diseased as far back as 1774. In his publication, he opined that fungi found associated with diseased tissues were separate living entities and did not emerge from dying tissues as hypothesized by other proponents.

GENESIS OF PLANT PATHOLOGY AS A DISCIPLINE

Initially the study of plant pathogens and diseases they cause were an aspect of botany or part of mycology, so plant pathology was initially called Applied Mycology. This idea persisted far into the 20th century until in 1883, in Copenhagen, Denmark, a plant pathology was established at the Royal Veterinary and Agriculture University to study plant diseases and their cause. By this time, plant pathology has gained relevance in the field of crop science in various universities across the world. One-person worth mentioning is Emil Rostrup, a professor at the plant pathology department, Royal Veterinary and Agriculture University, Copenhagen. He was a specialist of plant diseases at the time and mostly farmers' consultant. Among his notably works was a book he published in 1870 titled "*Om sygdromme hos de pa marken dyrkede planter"* simply put, diseases of field crops. By 1884, he has initiated comprehensive systematic survey of plant diseases of field crops. Many more of such pioneers in plant pathology are worth mentioning. Even though the initial objective of plant pathology was aimed at cataloguing and describing different plant diseases and their pathogens, attention was sooner turned towards their control and management. Diseases control, therefore became critical objective of plant pathology as science which continued with the study of the interaction between the host plant and the pathogens which added more to the body of knowledge as a discipline.

THEORIES OF DISEASE DEVELOPMENT

Disease Triangle

The disease triangle is the demonstration of the pressure the pathogen exerts on the host plant with the favor of the environment which pushes the plant to succumb to the pathogens attack. Diseases jeopardize effective ecological restoration and agricultural yield as a basis for food supply. The disease triangle is therefore the key structure in plant disease development that delineates the necessary circumstances for disease occurrence in any plant system. The three essential factors for disease development are: a host plant which is susceptible, the presence of a potent pathogen, and the environment that favors the pathogen (Velasquez et al. 2018; Xiang et al. 2021; Bernardo-Cravo et al. 2020). A disease could only be established if the three factors interact with each other. No disease is established if there is no interaction between these tree factors or there is interaction between any of the two factors but except one (Fig.1).

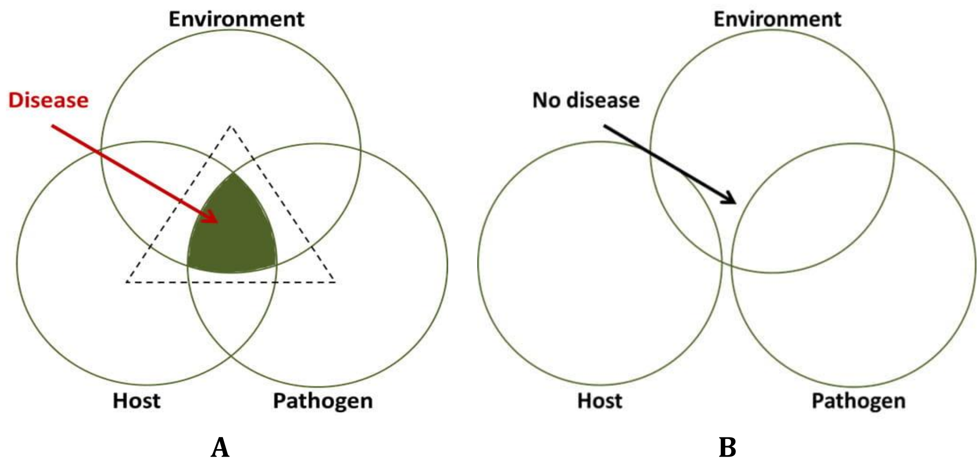

Figure 1: Disease Triangle (A: The system in which there is a susceptible host to disease in close relationship with the pathogen under suitable environmental conditions, B: System in which the host exhibits disease resistance despite being in close relationship with the pathogen under suitable environmental conditions.

The manipulation of the disease triangle by the pathologist in favor of the host will guarantee host resistance, prevention/protection or eradication of an already established disease. These could be done in variable ways including but not limited to placing a barrier of resistance between the host and the pathogen (genetic manipulation), making the pathogen less potent through application of chemical, biological or cultural means and varying the planting time, depth of seeding, protecting the host through weed control etc. The conditions affecting cultivation and establishment of host plant through the lens of the disease triangle are explored below:

Host:

The host plant is the most important figure in the disease triangle through which diseases are established or not. Without the host the pathogen might not have anything to associate with and derive nutrient from. The host therefore serves as a safe habitat for the pathogen. For such association to be fruitful, the basic requirement of the host is the need to guarantee sufficient nutrient for the pathogen survival for the period of association which is determined by the life cycle of the host. Again, the host should be predisposed for infection/susceptible and at the same time should be at the physiological state conducive for the pathogen attack. A "host" in the disease triangle encompasses not just an individual tree or crop but also its associated population of endo and epiphytes. Tree crops harbor abundant microbial life, and the longevity of each crop in both forested and cultivated environments may depend on comprehending and managing microbial communities to enhance health and mitigate harmful illnesses. The enhanced mutualism hypothesis posits that non-native plant species may exhibit greater productivity in novel environments by circumventing certain resource expenditures (i.e., constitutive barriers and defense compounds) associated with the evolutionary arms race between native species and local endemic fungal species (Sheng et al. 2022). Consequently, an African crop, being indigenous to Africa, may thrive better in other continents due to the absence of endemic organisms that possess an evolutionary history of antagonism towards those species. The co-evolution hypothesis posits that specific species of microorganisms and plants that co-evolve in the same environment might, at best, establish symbiotic partnerships that increase fitness, and at worst, mitigate antagonistic interactions among the related plants and microorganisms. To harness the ecological and economic potential of crops within the landscape, it may be essential therefore, to choose locally adapted varieties, irrespective of lineage, that exhibit resilience to global diseases. It is with this background and many others including development of resistant cultivars that the pathologist has used the natural or existing microbial habitat on the native crop to control plant disease originated by pathogens. Again, the development of resistant cultivar has been the pivotal objective for the breeder and the pathologist to overcome the advancement of the course of the pathogen. The plants also in their natural habitats have different mechanisms that are used to ward off pathogens attack, being structural or production of phytoalexins, chemical substances produced by the plant on insertion of an attack by the pathogen. These chemicals even though natural, can be induced artificially to the advantage of the host.

Pathogen:

The pathogen is considered as the "attacker" in its association with the host. The objective of the attacker is to get hosted and derive nutrient from the host. The pathogen employs different mechanisms to enable it attack the host and this mechanism is considered a "virulent factor". The pre-conditions of this are, the pathogen must be in its virulent state, produce sufficient numbers, must be aggressive or potent enough, must be at its pathological state, and must have the environment in its favor. The disease terrain of crops in specific locations or ecological zones is distinct from that of their ancestors due to the global transportation of plants and pathogens and the environmental changes that have occurred at the landscape level over the past century. With the current global warming, the environment has more than before been in favor of the pathogen to strive. Both native and non-native pathogens are among the microorganisms of economic concern. A variety of pathogenic microorganisms both native and non-native are reportedly causing damage to indigenous and exotic plants in plantations, natural forests, and agroforestry systems across the globe, with a particular emphasis in Africa. There are approximately thousands of pathogens that affect trees in planted and natural forests worldwide and specifically northern, western, eastern, central, and southern African countries (Ghana, Kenya, Malawi, Mauritius, Morocco, South Africa, and Sudan) according to the Food and Agriculture Organization of the United Nations (FAO) (Graziosi et al. 2020; Bossu et al. 2020). Over one-third of these species are non-native invaders, while only half are identified as native organisms. Additionally, 15% of these species are of unknown origin. Many of these organisms not only serve as direct attackers of the plant but also are introduced by vector of other plant disease especially viruses. Nevertheless, there are other several plant pathogens being fungi, mycoplasmas, nematodes, bacteria, and parasitic higher plants that are constantly invading the tissues of the plants with prospect of acquiring nutrients from them and consequently causing disease to these plants otherwise innocent species. The pathogen is seen as the most aggressive among the factors that cause disease and if the environment favors it, then there is no mercy to the plant once it is proved to be susceptible. The pathogen employs various virulent factor such as toxins, enzymes and extracellular polysaccharides to advance its course. These virulent factors target the cells, cell walls and internal tissues respectively to enable the pathogen get access to their host. The pathologist therefore considers the pathogen as the number one enemy due to its interest in the host and has always been at the war front philosophically with the pathogen. As much as the pathologist try to overcome the pathogen, the pathogen more swiftly acts ahead of the pathologist. In Table 1 below are examples of some insect vectors and pathogens of some of our cultivated crops.

Table 1: Native and no-native insect vectors and pathogens in Africa

Species	Common Name	Host	Distribution
Insect Vectors			
Peregrinus maidis	corn planthopper	Maize (transmits maize mosaic virus)	Widespread
Laodelphax striatellus	brown planthopper	Rice (transmits rice stripe virus disease)	Widespread
Bemisia tabaci	silverleaf whitefly	Tomao (transmits tomato yellow leaf curl virus)	Africa
Chaetocnema pulicaria	Corn flea beetles	Maize (spreading of Bacterium Stewartia) to cause Stewart's disease	USA and other parts of the world
Native Pathogens			
Pythium splendens	Pythium root rot	*Eucalyptus* spp.	South Africa
Ceratocystis spp.	Wattle wilt		Africa
Mycosphaerella spp.	Mycosphaerella leaf blotch	Wheat	Africa
Non-Native Pathogens			
Phytophthora cinnamomic	Phytophthora root rot	Tomato, Eggplant	South Australia
Cryphonectria cubensis	Chrysoporthe canker	*Eucalyptus* sp.	South America
Erythricium salmonicolor	Pink disease	Cocoa, coffee, mango	South Australia

Source: Graziosi et al. (2020)

Environment:

A disease-friendly environment necessitates an unsuitable habitat for the establishment of the host and conditions that are conducive to the establishment and propagation of the pathogen. As much as the environment tries to play its oversight responsibility on both the host and the pathogen, the pathogen strikes better when the environment plays or is conducive in its favor. In the advent of climate change, the adaptation of both the host and the pathogen has been eschewed in the favor of the pathogen as against the host and therefore more new diseases are being emerged. Pathogens that are not considered even important has become problematic. Other environmental stressors, such as disturbance, competition, herbivory, or poor soil, water, or air pollution, can increase the susceptibility of host plants to disease in addition to temperature and precipitation. Effects on host tree and pathogen interactions can be long-term and consequential as a result of long-term climatic, edaphic, or other environmental changes. For both hosts and pathogens, these changes can affect nutrient availability, shift the conditions and timing of physiological stress and reproductive capacity, and/or result in changes in co-occurring biological communities that can have cascading effects on population dynamics and niche partitioning. In spite of the fact that the majority of plants are resistant to the majority of infections, the presence of multiple environmental stressors can render plants more susceptible to pathogens that would be regarded as minor under low-stress conditions, as well as organisms that may have commensal or mildly pathogenic relationships with the environment. The pathologist therefore as a matter of priority tries to manipulate the environment in favor of the host by trying to cause adverse changes in the environment such as soil manipulation, mitigating greenhouse effect, using irrigation, varying plant depth and times etc.

Disease Cycle

The development and perpetuation of the disease and the pathogen are the result of a series of more or less distinct events that occur in sequence. This sequence of events is referred to as a "disease cycle". The pathogen attack results in changes in the plant that are frequently associated with symptoms, as well as those in the pathogens. The disease cycle is a complex process that encompasses periods within a growing season and from one growing season to the next. The knowledge of the disease cycle enables the pathologist plan in an effective measure of controlling the pathogen in its association with the host plant. It also enables the pathogen to determine how long it can establish a feeding relationship with the host. The main events of a disease cycle include:

1. inoculation
2. attachment
3. pre-penetration and penetration
4. host recognition and infection
5. invasion and colonization (the pathogen’s growth and reproduction)
6. seasonal carry-over/ over seasoning of the pathogen.
7. dormancy

Inoculation:

This is when a pathogen comes into contact with a host plant, the inoculum either directly or indirectly get into contact with the host plant. It refers to any component of the pathogen that has the potential to induce infection. Spores, sclerotia, or mycelial fragments may serve as inoculum in fungi. The inoculum is always comprised of entire or part of bacteria, fungi, mycoplasmas, viruses, and viroids. The inoculum of a parasitic higher plants may be its seed or a fragment of the plant, and may be referred to as adult, larvae or egg for nematodes. During the off-season, the primary inoculum is the inoculum that persists and initiates the original infection during the growing season. The infections are referred to as primary infections. Secondary inoculum is the term used to describe the inoculum that is generated from these primary infections and is capable of disseminating the disease in the field under favorable conditions. The secondary inoculum usually causes epiphytotic. A pathologist in his effort, can prevent this first approach or contact by the pathogen. The various ways the pathologist does these include avoidance, exclusion, protection and resistance.

Pre-penetration:
All what happens before the pathogen is admitted is within this stage, from germination of spores/seeds, eggs formation as occurs in the case of nematodes, attachment, the recognition between the host by the pathogen and the pathogen by host (an early event that is not yet fully understood). Lack of specific recognition factors on the plant surface may impede the attachment of a pathogen. Lectins (proteins or glycoproteins) and specific oligo- and polysaccharides are examples of such factors in plants.

Penetration:
This is the pathogen's actual admission into the host plant. Different methods are employed by the pathogens to penetrate plant surfaces: Direct penetration through natural apertures, intact plant surfaces, and wounds and sometimes introduced into the plant by vectors constituting indirect penetration. Plants may not develop disease, despite the fact that many organisms penetrate the cells, and penetration does not always result in infection. These organisms are incapable of progressing beyond penetration. Infection can therefore be avoided at this stage if the host is made resistant or protected. Once the measures are put in place, the host may not recognize the pathogen as a partner in the relationship even though it might be accommodated, but the period of accommodation might be brief or short and the pathogen would not survive but die.

Infection:
At this stage, the pathogen contacts host cells or tissues, get accommodated and extracts nutrients from them after it is recognized by the host. The pre-condition to infection is the host plant becoming susceptible and the pathogen taking nutrients, growing and multiplying in a conducive environment in favor of the pathogen. Pathogens infiltrate hosts in a variety of ways and to varying degrees. Certain fungi generate mycelium that exclusively develops in the region between the cuticle and epidermis, while others generate mycelium that exclusively grows on the host plant's surface, delivering only haustoria to epidermal cells. The plant is invaded to varying degrees by pathogens, which develop and multiply within the plant tissues during infection. In general, penetration of fungi and other pathogens like the parasitic higher plants into tissues happen by growing into them from a single initial point of inoculation. In order for a pathogen to infect a plant, it must be able to enter and traverse the plant, extract nutrients from the plant, and neutralize the plant's defense mechanisms. Once infection has occurred or been established, the only available option at the pathologist's disposal is to control the infection either by eradication (chemotherapy or biotherapy).

Invasion, Colonization (Growth, Reproduction and Dissemination) and Over-Seasoning:
The pathogen has the potential to swiftly infiltrate adjacent tissues and organs as it continues to grow within and between cells of the host plant. Plant symptoms become apparent during this invasive stage. Eventually, a new collection of spores is generated on and within infected plant tissues. These spores have the potential to be reintroduced to adjacent healthy plants, where they can either instigate secondary disease cycles or over-season in a quiescent state as before.

The significance of understanding the disease cycle of a variety of diseases is readily evident when one considers that each stage in the cycle is necessary for the subsequent stage.

Consequently, the disease will be curtailed and halted if any component of the cycle is disrupted. A successful disease control effort, whether it be by the pathologist or the environment, is the disruption of the disease cycle at any stage.

Gene for Gene Hypothesis (GFG HYPOTHESIS)

The GFG hypothesis, which was devised by H. H. Flor around the 1950's, is predicated on the GFG interaction between the resistance (R) gene in the host and the avirulence (Avr) gene in the pathogen. This interaction theoretically corresponds to the antigen–antibody interaction in vertebrates (Gill et al. 2021). The host's defense mechanisms are activated by the recognition of Avr products by R-proteins. Based on an understanding of numerous R and Avr genes in a variety of cereal plants, numerous models have been devised to elucidate the biochemical and molecular underpinnings of the gene-for-gene relationship. Flor (1951) discovered that "For each gene that determines resistance in the host, the pathogen has a corresponding gene with which it specifically interacts." In this scenario, the occurrence of a resistance reaction is contingent upon the presence of genes for resistance in the host and the corresponding genes for avirulence (non-infectivity) in the pathogen and vice versa. In a single gene interaction model, resistance is typically dominant, leading to host phenotypes R (resistant) and rr (susceptible), while infectivity is recessive, resulting in pathogen phenotypes V (non-infective) and vv (infective—referred to as "virulent"). In multi-gene models, the same fundamental principles are applicable.

Nevertheless, it is vital to recognize that resistant reactions that are produced by a particular GFG combination are typically interferes with or masks the expression of other genes in nature, in contrast to susceptible reactions that are the result of other combinations of host and pathogen genes (Thrall et al. 2016). Or, in other terms, resistance at one locus will obscure susceptibility at another. Genetic data in plant-pathogen associations has provided robust support for the GFG model. The isolation and mechanistic comprehension of genes that regulate plant immune responses to pathogens have provided the most convincing support. GFG type interactions between the host and its potentially numerous pathogens and parasites are rooted in the extensive variation that occurs in the corresponding host and pathogen genes. In a variety of plant-pathogen interactions, including bacterial, fungal, virus, nematode, and insect parasites, these interactions have been molecularly defined. On the other hand, they are especially pertinent to pathogens that are biotrophic or hemi-biotrophic and rely on living host cells for at least a portion of their infection cycle (Whitham et al. 2016; Krishnaraj et al. 2022). Rather than vertical resistance, plant pathologists strategically develop horizontal resistance with the gene-to-gene hypothesis in mind.

Disease Epidemiology

Although plant diseases frequently occur in the field, farmers do not apply pesticides promptly to control it upon spotting it. The threat of plant diseases to crop production can only be addressed when it surpasses a specific threshold (Gupta & Thind 2018; Jeger 2020). The genuine threat posed by plant diseases is their potential to spread like an epidemic. Epidemics are rapid and extensive, and they can result in a catastrophic reduction in the overall yield of crops if left unchecked (Rao & Raddy 2020; Jones 2021). This is the reason why the necessity of studying plant disease epidemiology is emphasized, as it will enable producers to identify the situation and factors that causes epidemics, and measures that must be implemented to prevent economic losses.

In disease epidemiology, certain key terminologies are important that need to be emphasized;

- **Epidemic:** Epidemic is a time-dependent increase in the incidence of disease within a population. A disease of such dimension can seriously affect a population within the shortest possible time.
- **Epiphytotic**: it simply refers to epidemics of plant disease.
- **Endemic:** disease that is indigenous to a specific location without a course to worry.
- **Pandemic disease:** A disease that occurs throughout a continent or region, it is a pervasive or worldwide occurrence.
- **Sporadic disease:** This is a disease that occurs at irregular intervals.
- **Exotic disease**: A disease which is imported from another region/country/continent.

Epidemiology considers all factors that contribute to the emergence of diseases, such as the length and intensity of environmental variables the aggressiveness of the pathogen, and the susceptibility of plants. The development of plant disease epidemics is the consequence of the timely convergence of the same elements that lead to plant disease: susceptible host plants, a virulent pathogen, and favorable environmental conditions over a relatively extended period. The initiation and development of epidemics may be unintentionally influenced by certain human activities. Pathologist may more frequently curtail the initiation and development of epidemics by implementing appropriate control measures in situations where epidemics would almost certainly occur. Therefore, the likelihood of an epidemic increases as the environmental conditions approaches the optimal level for pathogen growth, reproduction, and spread, as the susceptibility of the host and virulence of the pathogen increase, and as the duration of all favorable combinations is prolonged or repeated (Jeger et al. 2018).

THE PATHOGEN-CAUSAL AGENT OF DISEASES AND A FACTOR IN THE WARFARE

Perhaps the pathogen is the most intelligent among all the living things. They are the main causes of plant disease, deriving nutrient from their host for survival. They are usually referred to as infectious disease-causing agents or transmissible agents. Plants are prone to infection by thousands of species and with varying diversity. Among these are mycoplasmas, fungi, spiroplasmas, bacteria, viruses and viriods, nematodes, parasitic higher plants etc. These group of organisms use different mechanisms that enable them initiate contact, take nutrient and cause diseases in their host. This review looks at the overview of these pathogens.

Fungi

Wind, water, or invertebrate vectors are the means by which fungal spores as the main inoculum are dispersed. These spores have the capacity to adhere to a variety of surfaces, such as host or nonhost plants. Spores are prevented from washing away from the host surface prior to penetration by its attachment mechanisms. Firm adhesion to the host surface is contingent upon the secretion of the tenacious extracellular matrix from spores. The cycle of infection for plant pathogenic fungi starts from the emergence of a filamentous germ tubes and the germination of spores in favorable conditions. These processes necessitate the complete reprogramming of cells and the establishment of specific regulatory networks. Runner hyphae exhibit polarized cell development and grow along the host plant surface upon spore germination. The recognition of distinct physical (surface hardness and hydrophilic properties) and chemical (such as cutin and monomers, and leaf lipids) stimuli is essential for this growth.

Numerous phytopathogenic fungi possess a dome-shaped appressorium cell that enables them to quickly penetrate into the cuticle layer of their hosts. The appressorium cell is distinguished by a specially designed cell wall that has been enhanced with chitin and an interior layer that is covered with melanin (Chethana et al. 2021). It securely adheres to the host surface and applies a turgor-driven mechanical force to a thin penetration nail that ruptures the cuticle at the base of the appressorium and grows into the underlying plant epidermal cell. The peg's ability to penetrate host tissues is dependent on the physical pressure exerted by appressorial turgor and a specific level of enzymatic degradation of the host cuticle and cell wall. The site of host penetration is indicated by the hyphal tip enlargement of the infection hypha, which can be used to differentiate other pathogens. Nevertheless, this structure lacks a cell wall and is not fortified by melanization. Despite the fact that these structures are frequently referred to as appressoria, it is probable that the activity of lytic enzymes, rather than a mechanical force, will facilitate epidermal penetration from this type of infection structure. Another group of fungi species have evolved directional growth patterns on the host leaf surface to identify and recognize stomatal guard cells, which enables them to enter the hosts through a natural orifice (stomata). This group of pathogen causes most of the tropical diseases of plants and due to the degree of infection, plant pathology as science was referred to as Applied Mycology.

Bacteria

There are numerous methods by which bacteria can infect plants. Although a few instances of plant chemo-attractants have been reported, infection is generally regarded as passive, or accidental. Natural plant openings, including stomata, hydathodes, and lenticels, can be used to draw bacteria into a plant (Buttimer et al. 2017). They can enter through abrasions or lesions on leaves, stems, or roots, or through placement by specific feeding insects. The nutrient conditions in plants may be such that they encourage proliferation in various plant parts, such as flowers or roots. Inoculum that is transported by wind-driven rain can be highly efficacious. Artificially, bacteria are most commonly introduced into plants by wounding, by pressure-driven aerosols mimicking wind-driven rains, vacuum infiltration, or by seed immersion into inoculum (Chokheli et al. 2023). Bacteria resist control measures in multiple ways, they stop antibiotics from reaching its target or modify/bypass the target that the antibiotics acts on. Bacteria have the capacity to generate pumps that are located within their membrane or cell wall. These efflux pumps, which are prevalent in bacteria, are capable of transporting a diverse array of compounds, including signal molecules and nutrients. Additionally, certain of these pumps have the capacity to remove antibiotics from the bacterium, thereby reducing the concentration of antibiotics within the bacterial cell. In addition to the ability to add various chemical groups to antibiotics, bacteria can also produce enzymes that can inactivate or demolish them, such as β-lactamase, which destroys the active component (the β-lactam ring) of penicillin (Gritsch 2019). Bacteria can also camouflage the target of antibiotics, changes in the composition or structure of the target in the bacterium which sometimes results from mutations in the bacterial DNA, can stop the antibiotic from interacting with the target (Cao et al. 2019). Bacteria occasionally have the ability to reprogram the target of antibiotics by generating a distinct variant of the structure they require (Monserrat-Martinez et al. 2019).

Above all these, some bacteria are naturally resistant to certain antibiotics. Some antibiotics are made to target cell walls of the bacteria and if the bacteria do not have a cell wall, imagine the outcome. The bacteria are basically the main pathogens of diseases of crops in the template regions and are basically managed by the existing control measures such as chemical (bactericides), cultural and therapy.

Viruses

Currently, it is believed that over one thousand viruses have the potential to infect crops. Historically, it has been acknowledged that the symptoms of viral diseases may be the result of a toxic effect of certain virus components. Regrettably, the molecular basis of this effect is only known in a small number of instances. The induction of plant "suicide" defense in response to host resistance is an exception. Liu et al. (2021) and Brown et al. (2021) have established sophisticated strategies for viruses to interact with and manipulate host proteins in order to complete their life cycle within plant cells. Interactions between these proteins directly disrupt the functions of host proteins, which in turn disrupt a variety of cellular processes. Alterations in the cell cycle, hormone modulation, accumulation of reactive oxygen species (ROS), and chloroplast process dysfunction comprise these disruptions. As a consequence, these molecular disturbances lead to the development of viral symptoms (Yang & Wang 2021). Recent studies have shed light on the complex molecular processes that underlie the development of viral-induced symptoms, revealing the intricate interactions between plant viruses and host factors. A series of host responses can be triggered by viral infections, in addition to directly influencing cellular processes. Upon entering a plant cell, the virus employs the host biosynthetic machinery to synthesize its proteins and nucleic acids, while simultaneously redirecting the host's energy and nutrient resources to locations that are critical for virus replication and assembly (Nagy & Lin 2020). The typical physiological activities that occur within the plant cell are also disrupted by this redirected resource allocation. Simultaneously, the host modifies its metabolic pathways and gene expression patterns to accommodate the stress induced by viral infection. However, this reprogramming may also have detrimental effects on the physiological processes and development of the plant, which may lead to the development of symptoms associated with viral infection. The viruses are the most difficult to manage since they usually don’t respond to the usual control measures especially the chemical control except by the cultural practices.

Nematodes

Nematodes are prevalent soil pests that have an impact on vegetation. The aboveground symptoms of nematode-caused disease can be challenging to identify and are frequently misdiagnosed as those of nutrient deficiency (Singh et al. 2020). Plants are typically not thriving, appear paler than usual, and may wilt in the heat of the day. Plants that are afflicted frequently exhibit diminutive stature and diminutive foliage. Occasionally, the aboveground portions of infected plants may appear healthy, particularly when they are growing in moist, fertile soil or during cool weather. *Meloidogyne* spp. (root-knot nematode), *Pratylenchus* spp. (root lesion nematode), and *Heterodera* spp. (cyst nematode) are species that are known to directly infect crops, despite the fact that many nematodes serve as vectors (Mitiku 2018). The formation of galls or knots on plant roots because the ability of the plant to assimilate water and nutrients can be significantly influenced by root-knot nematodes. Root lesion nematodes penetrate the roots of plants, resulting in lesions that can progress to root rot as fungi and bacteria penetrate the damaged tissues. These nematodes are particularly detrimental to plants due to their ability to not only inflict direct damage to the roots but also to establish entry points for other pathogens, thereby exacerbating plant diseases.

Parasitic Higher Plant

Certain higher plant forms reside on the surface of other plants and frequently induce adverse reactions in their hosts. The epiphytes, hemiparasites, and genuine parasites are the three categories into which these plants can be classified (Schulze et al. 2019; Dauncey & Larsson 2018). Epiphytes primarily rely on their host plants for physical support and protection, causing them minimal to no damage. Hemiparasites, which are occasionally referred to as water parasites, do cause damage to their host plants by ingesting water and mineral nutrients. Nevertheless, they are endowed with chlorophyll and are capable of producing their own carbohydrates through photosynthesis. True parasites are devoid of chlorophyll and rely on their hosts for all of their sustenance, including carbohydrates, minerals, and water (Kumar et al. 2017). A valuable framework for comprehending parasitic plant–host plant interactions, particularly during the post-attachment phase of the interaction, is provided by numerous aspects of the models used to characterize the interaction of microbial pathogens with their host plants. At present, there is a lack of understanding regarding the mechanisms by which parasitic plants evade or suppress plant immunity as a result of their release during haustoria penetration.

Chemical Weapon Use by the Pathogen-The Virulent Factor

In an effort to unravel mechanisms by which pathogens cause diseases in plants as a second step in diseases management, scientists sought to understand various mechanisms through which pathogens accomplish these. As early as in 1886, DeBary reported the use of enzymes and toxins produced by *Sclerotinia* spp. that degrade and kill plant cells to obtain nutrient from their host when working on the Sclerotinia rot disease of carrot and other vegetables. Another eminent scientist who demonstrated the use of cytolytic enzymes involved in other soft rots of vegetables caused by bacteria was R. L. Jones in 1905. Around same decade in 1915, there were reports of pectic enzymes responsible for plant diseases among them was cellulase which was implicated in disease development. Diverse virulence factors, such as effector proteins, secondary metabolites, and even small RNA molecules, are essential for the establishment of diseases on their host plants. These virulence factors may be involved in the acquisition of nutrients, the prevention or suppression of host defenses, and the penetration of the host. Morphological transitions are also necessary for the virulence of plant pathogens to establish host colonization and complete their life cycles, in addition to these factors. Conversely, plants have developed a variety of innate immune systems to protect themselves from pathogen infection. In order to effectively infect plant hosts, these pathogens with varying lifestyles employ a variety of strategies and/or virulence factors to manipulate the physiology of host plants, thereby interfering with plant immune systems and promoting virulence or compatibility. Among these are:

Toxins:

Endotoxins:

There is a combination of different lipopolysaccharide components in this toxin that are toxic and found in the outer membrane of Gram-negative bacteria. Endotoxin has the potential to be lethal and has profound biologic effects on the host. Endotoxin must be eliminated from all medical supplies intended for injection or use during surgical procedures due to its ubiquitous presence in the environment (Rietschel & Westphal 2020).

Exotoxins:

Exotoxins, unlike the lipopolysaccharide endotoxin, are protein toxins released from viable bacteria. They are a genus of poisons that are among the most potent of all toxic substances, per unit weight. Unlike endotoxin, which is a structural component of all Gram-negative cells, exotoxins are produced by some members of both Gram-positive and Gram-negative genera. Generally, exotoxins have been exceptional antigens which elicit certain antibodies, which are referred to as antitoxins. While not all antibodies to exotoxins are protective, certain ones interact with critical binding or enzymatic locations on the exotoxin, leading to the total blockage of its deleterious activity (Rietschel & Westphal 2020). *Bacillus cinerea* produces botrydial, the most well-known non-host-specific sesquiterpene phytotoxin, during plant infection (Huo et al. 2018). Botrydial induces chlorosis and collapse of bean tissues, as well as necrosis in *Amaranthus thaliana* leaves.

Mycotoxins:

Fungal pathogens have the ability to secrete a diverse array of secondary metabolites, such as mycotoxins and secretory proteinaceous toxins, which result in cell death and contribute to the pathogenicity of plant hosts. General toxins and host-specific toxins (HSTs) are the two categories into which these toxins can be classified. Oxalic acid (OA) is another well-known non-host specific toxin that is considered an important pathogenicity factor in *Sclerotium. sclerotiorum.* In order to swiftly eliminate host plants, this pathogen secretes copious quantities of OA. A limited number of pathogens that are specific to a particular host produce HST proteins. By interacting with their host targets and utilizing plant resistance signaling pathways, these proteins can function as effectors, thereby facilitating infection by inducing host resistance and/or plant cell death. *Cochliobolus victoriae* is the source of victorin, a prevalent HST (Huo et al. 2018).

Cell Wall degrading Enzymes (CWDEs):

Xyloglucanases, polygalacturonases, glucanases, cellulases, and pectinases are examples of cell wall degrading enzymes that are used by fungal pathogen against cell walls degradation of plants. These categories of enzymes are important in primary structures of polysaccharides degradation of plant cell walls made of cellulose, hemicellulose, and pectin.

Effectors:

Effectors are molecules of pathogens that influence host response. Effectors are basically important during fungal penetration as pathogens which inhibit plant defense responses and/or to normalize the host's life (biotrophic effectors) or death (necrotrophic effectors) due to the lifestyle of pathogens been either biotrophic or necrotrophic (Zhang et al. 2022).

THE PATHOLOGIST-THE CONTROL STRATEGIST

The pathologist is considered as the control strategist in the fight of the pathogen to overcome its aggression over the host. The pathologist in his effort to fight the pathogen has designed various strategies or control options including chemical, biological, improving cultural practices aimed at avoiding or starving the pathogen, incorporation disease resistance genes into crop varieties through conventional breeding or through genetic engineering or the use of non-toxic compounds that could activate the natural plant defense systems. This part of the review discusses the various phases through which the pathologist designed the various strategies to combat the pathogen.

Descriptive Phase

The fight for supremacy between the pathologist and the pathogen begun during the descriptive era. Long before modern contributions, researchers who developed the interest in plant diseases made seminal contributions to the pathogen theory of disease. Pasteur and Koch contributed to the understanding of the precise causes of maladies in both humans and animals but not in plants (Pandey 2001). Regrettably, this historical lacuna has not been recognized in the biographies of significant figures, nor in the fundamental textbooks on the history of biological sciences and microbiology. For an extended period, there has not been a depth of knowledge exchange between botanists and zoologists in relation to the diverse disciplines of the biological sciences. It is indicative of the persistent inability by scholars in the biological sciences and microbiology to recognize the shared genetic bonds that exist between parasites of plants and animals. This could have resulted in delays in the beneficial application of knowledge that could have been prevented if these gaps had not existed. Koch and Pasteur are appropriately recognized as the individuals who provided the definitive evidence for the germ theory of disease in humans and animals (Egerton 2013). However, Lederberg (2000) noted in an argument of infectious disease that medical microbiology emerged as a distinct field from the general biological and plant sciences. For example, bacteriology was initially taught almost exclusively in medical institutions, which effectively isolated it from the advancements in the field of fundamental genetics and general biology. In a similar vein, plant pathologists have focused on their own field. In 1914, L.R. Jones, one of the early intellectual leaders in plant pathology, urged his colleagues to adopt a more in-depth, cross-disciplinary approach to research on the relationship between hosts and parasites. The absence of scientific cross-pollination is predominantly due to the fact that plant pathologists disregarded the call.

This period was characterized by the advancement of techniques, inventories of ideas, and theories for the study of Plant Pathology. Brefeld, Koch, Petri, and other prominent figures introduced techniques for culturing microorganisms (fungi and bacteria) in pure cultures. This occurred between 1875 and 1912 and had a substantial effect. Koch's postulates, for example, had a significant impact in 1887 in that, they established a prerequisite for the acceptance of a specific pathogen isolated from an afflicted plant as the cause of the disease. The histopathological and cytological studies of infected plants were significantly influenced by the discovery of advancements in plant tissue-staining techniques and compound microscopes, which facilitated the identification of pathogens in plant cells and tissues. The electronic microscope enabled the description and visualization of the majority of viruses by the 1940s, which facilitated the identification and description of mollicutes and viroids after the 1970s. It is in the same period that the biology of many microorganisms, types of spores produced by these microbes, the means of infection and spread, location of their over-seasoning structures, kind of host preferred, environmental factors that contributed to disease development as well as trials of control measures mainly cultural and chemical were all initiated, which culminated in the discovery of Bordeaux mixtures as one of the powerful fungicides of all time.

Experimental Phase

This era is the era of recognition of plant pathology as a discipline and a profession. It opened for the opportunity for plant pathologists to be recognized. It also opened up for scientists of plant health to experimentation in all areas of plant pathology. New diseases and pathogens were discovered and described, more questions were asked and experiments were designed to answer those questions. Notably among them were how pathogens enter their hosts, how they multiply and spread within their host, mechanisms through which host cells breakdown and die or vice versa among many others. Question of variability among plant species and how diseases are expressed among varieties of host were also answered. All these led to the rapid growth of knowledge in plant disease control and to avoid or reduce losses that otherwise may have occurred through plant diseases.

Etiological Phase

This era involved observations and experimentations to providing the causes of plant diseases at the time. This era not only began to give proof of pathogenicity of certain diseases eg. Potato late blight, rust and smut diseases of cereals but also improved techniques for culturing fungi and bacteria to satisfy Koch postulate for all diseases. Description of many symptoms of most diseases were also accomplished as well as efforts to isolate and culture most pathogens to prove their pathogenicity. Many pathogens were also identified to be non-culturable such that they appeared dead outside their host and considered as obligates. All these were done to improve ways that plant diseases can be controlled to avert the losses in crop production.

Recent Advances in Identification of Pathogenic Agents:

New and advanced laboratory methods for the identification of plant pathogens, particularly bacteria, viruses, and viroids, have been developed as a result of advancements in the use of microscopes, serology, boasting defense mechanisms (immunology), molecular biology, and laboratory instrumentation. Other techniques such as immunosorbent electron microscopy and scanning tunneling microscopy have been developed to improve the sensitivity of antigen-antibody detection. More practical genetic studies have been made possible due to the use of Radioimmunoassay (RIA) and enzyme-linked immunosorbent assay (ELISA) techniques. Radioactive labeling as a DNA hybridization technique, for instance, is used for a DNA strand from an already identified species with one from an unidentified species, has made characterization and identification of bacteria more practicable. Another area that has seen some development is the Automated Technology which performs large tests more quickly on specimens, which provides for an automatic analysis of results (Sastry 2013; El-Sheikha et al. 2018).

Search for Control of Plant Diseases

Far before the development of searching for plant disease control, significant recommendations for the control of plant diseases had been made in many reports far back as 1000 BC, 470 BC and 300 BC by ancient Greek Homers, Democritus and Theophrastus respectively. However, it is until the mid-1600s that some varieties of plants/crops were reported to be resistant to diseases. This gave course to belief that at the time growers had been using selection as a means of disease control. This is on the premise that if one could get seed to plant, it is due to the fact that only surviving plants will have their seeds available for planting but not those that are destroyed by diseases. The first chemical for the control/treatment of seed from smut disease was the rescue of wheat seeds from ship wreckage in England during the 1600s when farmers realized upon planting that, such seeds were free from the disease comparable to those which were not rescued from such wreckage and so they began to treat seeds with sea water of sodium chloride solution (blime) to control smut disease and subsequently it was substituted with copper sulphate in the 1700s as it improved suppression of smut disease tremendously.

Control Era

The goal of the control era was to either shield the host from the pathogen or eradicate an already established pathogen from the host by establishing a barrier between the pathogen and the susceptible portion of the host. This was achieved through the regulation of the environment, the control of insect carriers, the administration of chemical pesticides, and the implementation of cultural and handling practices. These practices were premised on the six disease control principles including exclusion, avoidance, eradication, protection, use of resistant/selection and therapy, and more extensively the integrated disease management which encompasses all the other control options with rational use of chemicals. This review looks into more details some of these management options.

Regulation of the Environment

Selecting outdoor growing areas with unfavorable weather conditions for the disease can control disease by regulating the environment. For example, growing potato seed crops in northern temperate regions with low temperatures can prevent viral infections. This is to exclude from the area or avoid the pathogen from getting access to the host even though the pathogen might be present at the area.

Breeding for Host Resistance or Innate Immunity Against Pathogens

Consequently, plants and/or parasites are compelled to develop mechanisms that enable them to gain a competitive advantage, as there is an ongoing coevolutionary arm race between them. Van der Plank (1963) was the first epidemiologist to provide a comprehensive theoretical foundation for the concepts of resistance. The concept of general (race-nonspecific) resistance and its implementation in crop improvement experienced a resurgence in the late 1960s and 1970s (Patterson 2022). In plants, there are numerous surface receptors, with pattern recognition receptors (PRRs) being particularly important. These receptors are designed to identify conserved pathogenic determinants, known as pathogen-associated molecular patterns (PAMPs), and to initiate a typical weak broad-based quantitative defense response known as PAMP-triggered immunity (PTI) against the pathogen(s). Pathogens that surpass the production or delivery of proteins, known as effectors, to impede or impede PTI in order to obtain an advantage in the race. However, plants have developed methods to thwart pathogenic designs by employing a different set of receptors, the resistance proteins (R-gene products). These proteins directly or indirectly detect the effectors, enabling the second line of defense, which is typically a stronger race-specific qualitative defense response known as effector triggered immunity (ETI) (Thomas 2022).

Cultural Practices

An effective cultural practice that mitigates the impact of disease is the selection of the optimal time and depth for seeding and sowing. It is possible to cultivate cool-temperature crops in soils that are contaminated with root knot nematodes and harvest them before the soil temperatures become appropriate for nematode activity. Another cultural practice of extensive utility is the adjustment of soil moisture. For instance, excessively moist soils are conducive to seed decay, damping-off (the devastation of seedlings at the soil line), and other seedling diseases (Khrieba 2020). The utilization of ridges or gardens for plants and the presence of drain pavers in fields with inadequate drainage are frequently advantageous. The control of certain maladies is also achieved through the adjustment of soil pH. The pH can be adjusted to 5.2 or lower to control common potato disease; however, other acid-tolerant plants must be incorporated into the crop rotation (Lambert et al. 2005).

Regulation of Fertility Level and Nutrient Balance:

The incidence of specific bacterial, fungal, and viral diseases in maize, cotton, tobacco, and sugar beet may be influenced by the balance of potash and nitrogen. Numerous crop and ornamental plants may develop noninfectious maladies as a result of a variety of microelements, such as boron, iron, zinc, manganese, magnesium, copper, sulfur, and molybdenum. A corrective measure is the application of chelated (bound or encapsulated in large organic molecules) or soluble salts to the soil, the adjustment of soil pH, or the sprinkling of foliage with these or similar salts (Chhabra & Chhabra 2021).

Biological Control

The use of organisms, their parts or metabolic by-products other than that of humans to reduce or prevent infection by a pathogen in plants is known as biological control of plant diseases. These organisms involve are refer to as antagonists. Antagonists are organisms that may naturally occur within the host's environment or be intentionally applied to specific regions of the potential host plant where they can directly or indirectly affect the pathogen (Feichtmayer et al. 2017; Dukare et al. 2019). Despite the extensive observation of the effects of biological control, the mechanisms by which antagonists achieve control remain incompletely comprehended. Various methods have been observed: certain antagonists produce antibiotics that either eliminate or reduce the number of closely related pathogens; others are parasites on pathogens; and others simply compete with pathogens for available food or limited resources. According to Hajek (2018), cultural practices that benefit from a naturally occurring antagonists and capitalize on its beneficial effects are frequently effective in reducing disease. Numerous antagonists that are more specific are currently being investigated and show significant potential for the future management of diseases.

The Use of Genetic Engineering in Developing Disease-Resistant Plants

The process of genetic engineering entails the manipulation of cell genetic material to generate novel characteristics in organisms. Transgenic organisms are generated by incorporating genes from other species into their genomes, resulting in the presence of recombinant DNA from other species. This approach has resulted in the development of plants that are resistant to pathogens and tolerant to herbicides. As a result of environmental concerns, precautionary measures have been implemented to safeguard this technology (Glick & Patten 2022).

Chemical Use in Managing Diseases

Chemicals are employed to manage plant diseases by inhibiting or eliminating pathogens. These consist of nematodes (nematicides), fungi (fungicides), and bacteria (bactericides). Eradicants eliminate pathogens in soil, seedlings, or propagative organs, whereas protectants establish a chemical barrier (Ul-Haq et al. 2020). Therapeutic compounds are employed to mitigate the progression of an infection. Nematodes, fungi, and microorganisms that inhabit the soil are eliminated by soil treatments. The soil is treated prior to sowing; however, certain fungicides may be combined with it during the planting process. Foliage and fruit are safeguarded by protective mists and dusts; however, they may be eliminated by wind, rain, irrigation, or sunlight. New chemicals are perpetually being created (Theuretzbacher & Piddock 2019). The use of chemical is either to avoid the pathogen, protect host plant or eradicate the established pathogen in a susceptible host.

Public Concern About Chemical Control

Many toxic chemicals were formulated to control plant pathogens which at the time were not only effective but the most potent and faster/rapid in their action, but it became so obvious that the initial intention of their usage were defeated as it did not only become toxic to the pathogens which were the pathologist's target but also higher animals including humans at even lower concentrations as water bodies, foods were all contaminated. This negative effect though did not defeat the initial objectives with its obvious benefits and tremendous impact in controlling insects and diseases in plants but raised much public concerns.

Main Areas of Progress of Chemical Control

Control of diseases with chemicals has had high level of success over the years despite its shortcomings such as environmental pollution, resistance to target pathogen, indiscriminate death to beneficial organisms and effect on human health. Chemical control has been an integral part of crop production all over the world with the ultimate aim of increasing yield, farmers income and ensuring food security. Studies have shown that without chemical control of plant diseases, production of crops is highly impossible (Cuthbertson & Murche 2003; Gianessi & Reigner 2005). The search requirement for new chemicals for control of plant diseases include a novel mode of action against major diseases as well as low risk of occurrence of resistance and minimal levels of toxicity/risk. Most recent chemicals are geared towards site-specific, acting against pathogens at a single binding site in biochemical pathways. Typical examples are the sterols biosynthesis inhibitors such as triazoles respiration inhibitors (strobilurins and carboxamides), cellulose biosynthesis inhibitors eg. carboxylic acids, amides etc. which make the current crop of chemical products safe since such target pathways do not exist in mammals, eliminating the risk of contamination. However, development of chemical resistance can be compromised in such situation due to the nature of mode of action, the pathogen biology as well as the genetic changes needed to adapt to the chemical. The good news therefore is that the new chemical products are geared towards to cause minimum risk to operators, consumers and the environment.

Alternative Control of Plant Diseases:

Due to the public outcry of the danger of using chemical pesticides, attention of the pathologist shifted towards the search of alternative control that were less toxic to higher animals and humans as well as reducing its negative environmental concerns. This led to re-examining old methods of farm practices that could control pest and diseases. Proper cultural practices involving the removal of plant debris and infected plant parts, use of pathogen-free seeds, crop rotation with plants species that are immune to certain pathogens, destruction of weeds that serve as alternative host and minimal use of chemicals as and when necessary, culminated in the concept of integrated diseases management, a package that harness the potential of all control measures but rational use of chemical as and when necessary.

KEY CONTRIBUTORS IN ADVANCE OF THE WARFARE BETWEEN THE PATHOLOGIST AND THE PATHOGEN

Over the course, many scientists have made notable contributions to plant pathology. The following are short biographies of few of those attempts to highlight some of the most prominent findings all in an effort to bring under control the exigence of the pathogen.

Heinrich Aton de Bary, 1831

De Barry is known as the father of plant pathology. The German discovered the cause of potato blight and founded modern mycology and the study of moulds.

Nathan Augustus Cobb, 1859–1932

The progenitor of nematology in North America. His contributions encompassed the description of over 1,000 species and advancements in the comprehension of nematode anatomy. In 1913, he initiated the publication that contributed to a Science of Nematology and devised microscopic methods and sampling/extraction techniques of nematodes.

Ruth Florence Allen, 1879–1963

She conducted research on the cell of rust fungi, which was instrumental in the development of an understanding of disease within plant tissue. This advancement significantly expanded our understanding of rust fungi.

Elvin Charles Stakman, 1885–1979

The discovery of physiological races of rust, which Stakman assisted in characterizing, resulted in an endeavor to breed wheat that was resistant. In 1918, he was also instrumental in the inception of the program to eradicate barberry bushes, a significant endeavor to extinguish this alternate host for the black stem rust pathogen.

James Geere Dickson, 1891–1962

He focused his research on a diverse array of pathogens and diseases, with a particular emphasis on cereal and forage crops. He contributed to the development of soil temperature tanks, conducted research on Fusarium head scab, and investigated the impact of soil temperature on the seedling blight of wheat and maize.

Walter Hagemeyer Burkholder, 1891–1983

He played a pioneering role in the field of bacterial taxonomy by separating the main genera of plant-pathogenic bacteria that had previously been grouped under the genus Phytomonas. Bergey's Manual of Determinative Bacteriology implemented Burkholder's classification scheme. Agrobacterium, Corynebacterium, Erwinia, Pseudomonas, and Xanthomonas were the genera into which Phytomonas was divided by Burkholder's scheme. He also conducted research on bacterial physiology and created resistant bean cultivars. In 1949, he initially identified *Pseudomonas cepacia (Burkholderia cepacia)* as the source of onion bulb disease. In his honor, the genus Burkholderia is named.

Edna Marie Buhrer, 1898–1988

Edna Buhrer conducted research on nematode diseases for nearly 40 years, during which time the majority of producers were skeptical that nematodes could have a substantial impact on crops. Buhrer contributed to the description of the pinewood nematode and other significant species, publishing nearly 40 papers on plant nematology. She was also involved in the illustration of the developmental phases of the golden nematode (*Globodera rostochiensis*) shortly after it was discovered.

Kenneth Frank Baker, 1908–1996

Baker was a pioneer in the fields of biological control, soilborne pathogens, and nursery and ornamental pathology. In 1974, he jointly authored the first significant book on the biological control of plant pathogens with R. J. Cook, which was titled Biological Control of Plant Pathogens.

James Edward Vanderplank, 1908-1997

Vanderplank is known as the father of plant disease epidemiology. His work on how plant diseases spread and develop over time was groundbreaking. He is considered as the founding father of modern qualitative botanical epidemiology. His ideas and mathematical formulations changed the field of plant pathology and breeding and provided plant pathologists with tools to analyze epidermis. He introduced the simple and compound interest concepts into plant pathology.

George Aubrey Zentmyer 1913–2003

Zentmyer initiated his professional tenure as a forest pathologist, during which he conducted research on the biology and management of Dutch elm disease and white pine blister rust. Later, he became a global expert on Phytophthora as a result of his research on avocado disease. He introduced numerous novel concepts, such as heterothallism, chemotropism, and chemotaxis. He also employed biological control methods and ascertained the reason for their effectiveness.

Myron Kendall Brakke, 1921–2007

Brakke was a trailblazer in the field of virology and the biophysical properties of viruses. He introduced a new era of molecular biology and virology research in 1950 by developing density gradient centrifugation, an instrument that facilitated the purification of virus particles. Brakke collaborated with a wide variety of viruses, such as the Barley stripe mosaic, Potato yellow dwarf, Soilborne wheat mosaic, Tomato spotted wilt, and Wound tumor viruses.

John Michael Tresh, 1930-2015

Another epidemiologist known as the founding father of plant virus epidemiology. His work described major epidemics and pandemics of the plant viral diseases that occurred worldwide.

CONCLUSION

Mankind is faced with challenges in feeding a growing population of the world and require rapid increase in agricultural intensification and solutions to fighting the disease pathogen. Despite all human effort in technology, the yield required from crop production is far from achieving if pathogens are not controlled. This objective of producing disease free crops can only be achieved through advances in agricultural production systems such as improvement in natural and genetically modification of crop traits and new innovations in areas of crop protection. Diversity in pathogen insurgency and pathologist devising new areas of fighting pathogens to ensure continue increased production, control new threats from pathogens, lack of diversity of control options available to the producer to use in an integrated manner to produce sufficient food will therefore be a mirage. The issue at stake looked at how both the pathogen and the pathologist try to outwit each other in other to gain supremacy over the control of the plant. The debate cannot be concluded as both pathogen and pathologist try to make their way. Readers are therefore required to make their own judgement as who is ahead of the other but one thing for sure is that the pathogen is far ahead of the pathologist for want to establish this supremacy but the pathologist factor will still remain paramount. Are we making the needed progress? Your thought is as good as mine.

Conflict of interest

The author declares no conflict of interest

About the author

The author is an Associate Professor of Plant Pathology and Applied Microbiology in the Department of Crop & Soil Sciences at the Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED), Asante Mampong campus. He is currently the Head of Department at the Faculty of Agriculture Education. He has made several contributions to the body of knowledge in his area of specialization. His area of research interest is in Molecular Plant-Microbes Interactions (Biological control of Plant Diseases) with emphasis on the use of Secondary Metabolites of Rhizobacteria to control plant diseases.

References

Agrios, G. N. 2005. Plant Pathology, 5th Edition. Academic Pess, London. Pp .952.

Bernardo-Cravo, A. P., Schmeller, D. S., Chatzinotas, A., Vredenburg, V. T., & Loyau, A. 2020. Environmental factors and host microbiomes shape host–pathogen dynamics. Trends in Parasitol. 36(7): 616-633.

Bossu, P. P., Apetorgbor, M. M., Amissah, L., & Mutta, D. 2020. Status, trends and impacts of forest and tree pests in West and Central Africa. Afr. J. Rural Devt. 4(1): 93-107.

Brown Z. P., Abaeva I. S., De S., Hellen C. U. T., Pestova T. V., Frank J. 2022. Molecular architecture of 40S translation initiation complexes on the hepatitis C virus IRES. EMBO J. 41:e110581.

Buttimer, C.; McAuliffe, O.; Ross, R. P.; Hill, C.; O'Mahony, J.; Coffey, A. 2017. Bacteriophages and Bacterial Plant Diseases. Front. Microbiol,. 8: 1- 34.

Cao, Z., Cheng, S., Wang, X., Pang, Y., & Liu, J. 2019. Camouflaging bacteria by wrapping with cell membranes. Nat. Comm. 10(1): 3452.

Chethana, K. T., Jayawardena, R. S., Chen, Y. J., Konta, S., Tibpromma, S., Phukhamsakda, C. & Hyde, K. D. 2021. Appressorial interactions with host and their evolution. Fung. Div. 110(1): 75-107.

Chhabra, R., & Chhabra, R. 2021. Nutrient management in salt-affected soils. salt-affected soils and marginal waters: Glo. Persp. Sust. Man. 349-429.

Chokheli, V. A., Bakulin, S. D., Ermolaeva, O. Y., Kozlovsky, B. L., Dmitriev, P. A., Stepanenko, V. V.& Varduny, T. V. 2023. Investigation of growth factors and mathematical modeling of nutrient media for the shoots multiplication *in vitro* of rare plants of the Rostov region. Horticult. 9(1): 60.

Cuthbertson A. G. S., Murchie A. K. 2003. The impact of fungicides to control apple scab (*Venturia inaequalis*) on predatory mite *Anystis bac*carum and its prey *Aculus schlechtendali* (apple rust mite) in Northern Ireland Bramley Orchards. Crop Prot. 22: 1125-1130.

Dauncey, E. A., & Larsson, S. 2018. Plants that kill: A natural history of the world's most poisonous plants. Princeton University Press.

Dukare, A. S., Paul, S., Nambi, V. E., Gupta, R. K., Singh, R., Sharma, K., & Vishwakarma, R. K. 2019. Exploitation of microbial antagonists for the control of postharvest diseases of fruits: a review. Crit. Rev. Fd. Sci. Nutri. 59(9): 1498-1513.

Egerton, F. N. 2013. History of ecological sciences, part 46: from parasitology to germ theory. Bull. Ecol. Soc. Am. 94(2): 136-164.

El Sheikha, A. F., Levin, R., & Xu, J. 2018. Molecular techniques in food biology. John Wiley & Sons Ltd.: New York, NY, USA.

Feichtmayer, J., Deng, L., & Griebler, C. 2017. Antagonistic microbial interactions: contributions and potential applications for controlling pathogens in the aquatic systems. Front. Microbiol. 8: 2192.

Flor H.H., 1951. Genes for resistance to rust in Victory flax. Agron. J. 43: 527–531.

Gianessi L.P. & Reigner N. 2005. The value of fungicides in US crop production. Crop Life Foundation. www.croplifefoundation.org.

Gill, B. K., Bhatia, D, & Mavi, G. S. 2021. Eighty years of Gene-for-Gene relationship and its application in identification and utilization of R genes. J. Gen. 100(2): 50-67.

Glick, B. R., & Patten, C. L. 2022. Molecular biotechnology: principles and applications of recombinant DNA. John Wiley & Sons.

Graziosi, I., Tembo, M., Kuate, J., & Muchugi, A. 2020. Pests and diseases of trees in Africa: A growing continental emergency. Pl. Ple. Plt. 2(1): 14-28.

Gritsch, L. 2019. An investigation on antibiotic-free antibacterial materials combining bioresorbable polyesters, chitosan and therapeutic ions (Doctoral dissertation, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)).

Gupta, S. K., & Thind, T. S. 2018. Disease problems in vegetable production. Scientific Publishers.

Hajek, A. E., & Eilenberg, J. 2018. Natural enemies: an introduction to biological control. Cambridge University Press.

Huo, D., Wu, J., Kong, Q., Zhang, G. B., Wang, Y. Y., & Yang, H. Y. (2018). Macromolecular toxins secreted by botrytis cinerea induce programmed cell death in arabidopsis leaves. Rus. J. Pl. Physiol. 65: 579-587.

Jeger, M. J. 2020. The epidemiology of plant virus disease: Towards a new synthesis. Pl. 9(12): 1768.

Jeger, M. J., Madden, L. V., & Van Den Bosch, F. 2018. Plant virus epidemiology: Applications and prospects for mathematical modeling and analysis to improve understanding and disease control. Pl. Dse. 102(5): 837-854.

Jones, R. A. 2021. Global plant virus disease pandemics and epidemics. Pl. 10(2): 233.

Khrieba, M. I. 2020. Damping-off caused by Pythium species: disease profile and management. In Pythium (pp. 257-269). CRC Press.

Krishnaraj, P. U., Arun, Y. P., Namdev, C. D., & Jahagirdar, S. 2022. Molecular Basis of Host–Pathogen Interaction: An Overview. Fung. Div. Ecol. Ctrl. Mgt. 539-556.

Kumar, J., Singh, D., Ghosh, P., & Kumar, A. 2017. Endophytic and epiphytic modes of microbial interactions and benefits. Plant-Microbe Interactions in Agro-Ecological Perspectives: Volume 1: Fundamental Mechanisms, Mts Funct. 227-253.

Lambert, D.H.; Powelson, M.L.; Stevenson, W.R. 2006. Nutritional interactions influencing diseases of potato. Am. J. Pot. Res. 82(4): 309-319. https://doi.org/10.1007/BF02871961

Lederberg, J. 2000. Encyclopedia of microbiology, four-volume set. Academic Press.

Liu, S., Wang, C., Liu, X., Navas-Castillo, J., Zang, L., Fan, Z., ... & Zhou, T. 2021. Tomato chlorosis virus–encoded p22 suppresses auxin signalling to promote infection via interference with SKP1-Cullin-F-boxTIR1 complex assembly. Pl. Cell & Env. 44(9): 3155-3172.

Mitiku, M. 2018. Plant-parasitic nematodes and their management: A review. Agric. Res. Technol, 8(1), 30-38.

Monserrat-Martinez, A., Gambin, Y., & Sierecki, E. 2019. Thinking outside the bug: molecular targets and strategies to overcome antibiotic resistance. Intern. Journal Mol. Sci. 20(6): 1255.

Nagy, P. D., & Lin, W. 2020. Taking over cellular energy-metabolism for TBSV replication: The high ATP requirement of an RNA virus within the viral replication organelle. Vir. 12(1): 56.

Norrie, P. 2016. A history of disease in ancient times: More lethal than war. Springer.

OPEC Fund 2022. Contributing US$50 Million to pre-export facility for Ghana's cocoa crop fo the 2021/2022 crop season. OPEC Fund News. Parling 8, 1010 Vienna, Austria.

Pandey, B. P. 2001. Plant pathology (Pathogen and Plant disease). S. Chand Publishing.

Patterson, R. E. 2022. Tracking the Development of Common Bunt Colonization throughout the Plant Life Cycle in Compatible and Incompatible Reactions Using qPCR (Master's thesis, University of Idaho).

Rao, G. P., & Reddy, M. G. 2020. Overview of yield losses due to plant viruses. In Applied plant virology (pp. 531-562). Academic Press.

Rietschel, E. T., & Westphal, O. 2020. Endotoxin: historical perspectives. In Endotoxin in health and disease (pp. 1-30). CRC Press.

Sastry, K. S. 2013. Diagnosis and Detection of Plant Virus and Viroid Diseases. In Plant Virus and Viroid Diseases in the Tropics: Volume 1: Introduction of Plant Viruses and Sub-Viral Agents, Classification, Assessment of Loss, Transmission and Diagnosis (pp. 233-353). Dordrecht: Springer Netherlands.

Schulze, E. D., Beck, E., Buchmann, N., Clemens, S., Müller-Hohenstein, K., Scherer-Lorenzen, M., & Scherer-Lorenzen, M. 2019. Interactions Between Plants, Plant Communities and the Abiotic and Biotic Environment: With Contributions from CF Dormann and HM Schaefer. Pl. Ecol. 689-741.

Secoy, D. M., & Smith, A. E. 1978. Superstition and social practices against agricultural pests. Envtl Rev., 2(5), 2-18.

Sheng, M., Rosche, C., Al-Gharaibeh, M., & Bullington, L. 2022. Acquisition and evolution of enhanced mutualism-an underappreciated mechanism for invasive success? The ISME J., 16(11):1-12.

Singh, V. K., Singh, V., & Kumar, D. 2020. Nematode diseases of cereal crops and their management. In Diseases of Field Crops Diagnosis and Management (pp. 387-403). Apple Academic Press.

Theuretzbacher, U., & Piddock, L. J. 2019. Non-traditional antibacterial therapeutic options and challenges. Cell Host & Micr. 26(1): 61-72.

Thomas, P. 2022. Game of' Mones: Comprehending *Bemisia tabaci* MEAM1 Nymph-Based Resistance and Defense Phytohormone Signaling in Alfalfa. University of California, Riverside.

Thrall, P. H., Barrett, L. G., Dodds, P. N., & Burdon, J. J. 2016. Epidemiological and evolutionary outcomes in gene-for-gene and matching allele models. Front. Pl. Sci. 6: 1084.

Ul-Haq, I., Sarwar, M. K., Faraz, A., & Latif, M. Z. 2020. Synthetic chemicals: Major component of plant disease management. Plant disease management strategies for sustainable agriculture through traditional and modern approaches, 53-81.

United Nation's Report. 2019. The world's population is expected to increase by 2 billion persons in the next 30 years, from 7.7 billion currently to 9.7 billion in 2050. https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html. Assessed 14th November, 2024.1.30pm GMT.

Vanderplank, J.E. 1963. Plant Disease: Epidemics and Control. Academic Press, New York, 349 p.

Velásquez, A. C., Castroverde, C. D. M., & He, S. Y. 2018. Plant–pathogen warfare under changing climate conditions. Curr. Biol. 28(10): R619-R634.

Whetzel, H. H. 1918. An outline of the history of phytopathology. WB Saunders.

Whitham, S. A., Qi, M., Innes, R. W., Ma, W., Lopes-Caitar, V., & Hewezi, T. 2016. Molecular soybean-pathogen interactions. Ann. Rev. Phytopathol. 54(1): 443-468.

Xiang, Q., Lott, A. A., Assmann, S. M., & Chen, S. 2021. Advances and perspectives in the metabolomics of stomatal movement and the disease triangle. Pl. Sci. 302: 110-697.

Yang, X., Li, Y., & Wang, A. 2021. Research advances in potyviruses: from the laboratory bench to the field. Ann. Rev. Phytopathol. 59(1): 1-29.

Zhang, S., Li, C., Si, J., Han, Z., & Chen, D. 2022. Action mechanisms of effectors in plant-pathogen interaction. Intern. J. Mol. Sci. 23(12): 6758.