Journal of Advances in Biology & Biotechnology

15(1): 1-17, 2017; Article no.JABB.36690
ISSN: 2394-1081

Emerging Trends in Plant Protection in Nigeria

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Author's contribution

Author AOS designed the study, performed the statistical analysis, wrote the protocol, wrote the first draft of the manuscript and managed the analyses of the study. Author AOS read and approved the final manuscript.

Article Information

DOI: 10.9734/JABB/2017/36690
Editor(s):
(1) Moaed Al Meselmani, Department of Molecular Biology and Biotechnology, The University of Sheffield, South Yorkshire.
Reviewers:
(1) S.Sivanandhan, Loyola College (Autonomous), University of Madras, India.
(2) Juliana de Oliveira Silva, Universidade Federal de Goiás, Goiânia, Brazil.
Complete Peer review History: http://www.sciencedomain.org/review-history/21206

Review Article

Received 8th September 2017
Accepted 25th September 2017
Published 2nd October 2017

ABSTRACT

Emerging trend in plant protection stems from the strengthening of the old control methods to microbial control of pathogens. This is based on the beneficial interactions of microbes on plant's health, the mechanisms which include: pathogen suppression by microbial agents that could be through competition with the pathogen itself; antagonism in form of antibiosis, parasitism and then, predation. It could also be through probiotic action, which is plant growth production, elicitation of defense responses and induction of systemic acquired resistance or suppression of toxin production by the pathogen. The numerous examples of plant secondary metabolites (phytoalexins and phytoanticipins) reviewed here demonstrate that they constitute an important mechanism to stop the spread of phytopathogens in plants, both by acting as antimicrobials themselves or as elicitors of other defense responses. More interestingly, phytoalexins and phytoanticipins have been found active against pathogens and their use as 'antibiotic potentiators' or 'virulence attenuators' for the control of infectious diseases is promising. Hence, the progressing threat of pathogens leading to crop losses, food insecurity; attenuated poverty and the incessant need for crop protection, strengthen the importance of the research activities aimed at the isolation and characterization of plant secondary metabolites and the understanding of the mechanisms involved in the natural defences of plants against microbial aggressors. Emerging trends can also be viewed from the

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impact of environmental conditions on plant's resistance (whether constitutive or induced), integrated pest management strategies, biological control and cultural practices.

Keywords: Emerging trends; plant protection; bio-control; hypersensitivity response.

1. INTRODUCTION

Plants represent a rich source of nutrients for many organisms including bacteria, fungi, protists, insects, and vertebrates. Although lacking an immune system comparable to animals, plants have developed a stunning array of structural, chemical, and protein-based defenses designed to detect invading organisms and stop them before they are able to cause extensive damage [1]. Humans depend almost exclusively on plants for food, and plants provide many important non-food products including wood, dyes, textiles, medicines, cosmetics, soaps, rubber, plastics, inks, and industrial chemicals [1].

Plant Protection is a branch of agricultural science that devises ways and means of controlling diseases, pests, and weeds of crops and trees, as well as a set of measures used in agriculture and forestry to prevent and eliminate the damage done to plants by harmful organisms. It is also based on the data obtained by several agronomic disciplines like: agriculture, plant pathology, entomology, zoological, and botany. Plant Protection is also closely related to other sciences like meteorology, climatology; chemistry and physics, which provide the scientific basis of chemical and biophysical control methods, hygiene and toxicology, which study the direct and indirect effects of pesticides on plants and animals. Plant Protection plays an important role in the growth, yield and general health of plants [2]. The damage done to plants by pests and diseases constitutes approximately 20-25% of the potential world food crop yield [2]. This shows the importance of plant protection as a discipline.

Diseases and pests have been found to be very harmful to plants; this is to the extent that in the olden days, devastating attacks were regarded as a 'manifestation of God's wrath upon humanity'. Based on this, in the early 18th century attempts were made to classify plant diseases by the French Botanist J. de Tournefort. Also in the late 18th century, many experiments conducted by A. T. Bolotov in Russia, M. Tillet in France, F. Fontana in Italy, and J. Fabricius in Denmark demonstrated the contagiousness of a large number of diseases [3]. In the latter half of the 19th century, the German Scientist H. A. De Bary, the Russian Scientist M. S. Voronin, and others discovered new species of phytopathogenic fungi and studied their morphology and developmental characteristics. Researches on the general nature of harmful insects also appeared in the 19th century [4]. The tremendous damage done to the economy of many countries in the latter half of the 19th century by pests and diseases (including phylloxera, locusts, and potato blight) made it necessary to centralize research efforts and the ways of devising control measures. Hence, research in plant pathology and entomology was based on the principles and methods of controlling harmful organisms which were then improved. Russian Scientists such as N. M. Kulagin and N. V. Kurdiumov were the first to advocate the principle of comprehensive differentiated use of methods of plant protection and, above all, preventive methods, which generally are the most effective [4].

Then agro-technological method of plant protection was based on the use of general and specific farming practices to create ecological conditions. For instance, crop rotation was considered a very important measure because generally, continuous cultivation of any annual plant results in the concentration of pests and causative agents of diseases [5]. Their numbers can also be reduced by appropriate methods of cultivating the soil. For example, shallow plowing after harvesting the field, followed by late season plowing could help to destroy the causative agents of many diseases and wintering insect pests. Plowing and cultivation promote the activity of predatory insects (ground beetles, for example) that destroy pests living in the soil. The sorting and cleaning of seeds, growing of healthy planting stock, prompt culling of inferior or diseased plants, removal of crop residues, and control of weeds are of great value. Planting crops at the optimal times helps to prevent the vulnerable phases of plant development from coinciding with the periods of maximum activity of pests. The addition of fertilizer promotes plant growth and increases resistance to injuries. The biological method of plant protection also came up this century and it was based on the use of predatory and parasitic insects (entomophages), predatory mites (acariphages), microorganisms, nematodes, birds, mammals, e.t.c., to suppress or reduce the numbers of harmful organisms.

However, the methods of using parasites and predators of pests vary from one country to the other, in this way crop pests are controlled by pathogenic fungi, bacteria, and viruses. For instance, USSR in 1962 started the production of the bacterial preparation entobacterin (made from spores and protein crystals of *Bacillus thuringiensis* var. galleriae), which is effective against a number of leaf miners. While in Nigeria, the biological preparation of trichodermin, derived from the soil saprophytic fungus-antagonist *Trichoderma*, suppresses the causative agents of diseases of flax and cereal grains and cotton wilt when applied to the soil. In Nigeria, it has been discovered that root pathogens living together compete with each other so that less nutrient will be made available to the less competitive, which leads to its death [6]. In the United States Department of Agriculture, Agricultural Research Service, Sidney, MT, USA, Experiments were conducted to study the interaction of the two pathogens and their potential impact on each other's survival. In petri dish experiments, the growth of *C. beticola* was significantly inhibited when it was paired against isolate of *Pyrenophora teres* under dark conditions. However, *P. teres* failed to establish contact with *Cercospora beticola* when the cultures were exposed to light. Microscopic investigation has revealed cercosporin in *Cercospora* hyphal strands prior to contacts. Hyphal strands of both fungi were without noticeable damage under darkness. However, under light, the significant hyphal damages were observed on *P. teres* indicating *C. beticola* induced structural damage of *P. teres* hyphal cells prior to actual physical contact. These observations indicate that the two pathogens were able to successfully antagonize each other under specific abiotic condition (*P. teres* under darkness and *C. beticola* under light). The results suggest that potential manipulation of an abiotic condition may lead to successful management of primary inoculum of both pathogens [7].

Also, some groups of organisms have been proposed as playing important roles in the suppression of some diseases like wilts. These organisms include actinomycetes, *Bacillus spp* and *Trichoderma* spp. All these organisms have been found to biologically control diseases in plants in Nigeria [6,8,9,10]. The interactions between these organisms have been studied in the laboratory through their effects on plant growth and yield. For instance, the interactions between *Glomus etunicatum* (mycorrhiza), *Phytophthora infestans* (pathogen), and *Trichoderma viride* (a soil-borne fungal antagonist) on pepper seedlings as it affects their growth was found beneficial to the plant in moderating the severity of disease caused by *P. infestans* [11]. However, the effect of *Trichoderma viride* on the pathogen was found to attest to effective biological control of this pathogen [12].

Plate 1. Examples of entomophages

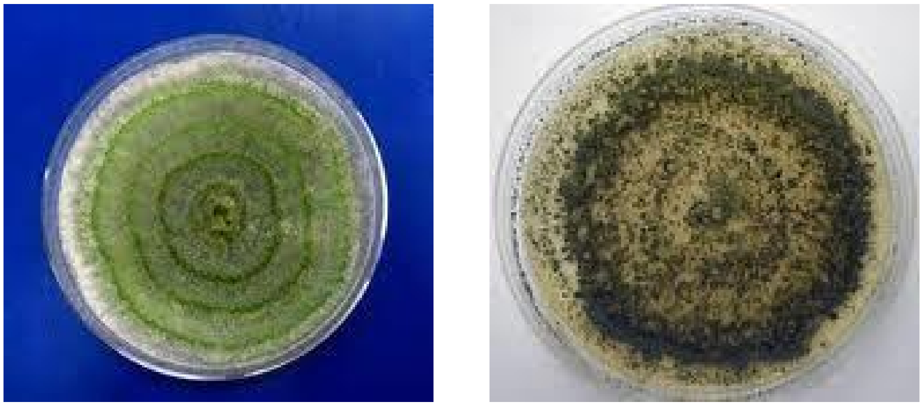


Plate 2. Cultures of *Trichoderma viride*
(Source: CPP Mycology Lab)

The chemical method of plant protection is based on the use of substances that are toxic to pests and disease causing organisms. A number of chemical compounds began to be widely used after 1945 because of their marked effectiveness, universality, and simplicity of use. The extensive and one-sided use of pesticides in many countries has had some undesirable consequences: pollution of the soil and natural water, appearance of pests' resistant to pesticides, accumulation of pesticides in food products, and so forth. Hence, steps are being taken all over the world to limit the use of pesticides, for example, establishment of maximum permissible levels of pesticide residues in food products and determination of the latest possible times for chemical treatment. The development of chemical methods of plant protection is associated with the National Environmental Standards and Regulations Enforcement Agency (NESREA) in Nigeria [13,14]. The mechanical methods of plant protection (use of barrier and trap ditches, sticky strips and various devices to catch pests) that once played an important role are now used minimally because they require much labor and are not very effective.

Recent advances in biology, physics, and chemistry are opening up new opportunities in the search for better methods of plant protection [15]. In the late 1940s the discovery of the adverse effects of the chemical method intensified interest in so-called integrated plant protection termed Integrated Pest Management (IPM); a combination of chemical and biological methods to preserve useful entomophages as much as possible and, in the broader sense, a rational combination of all methods to construct differentiated systems of protective measures. The ultimate objective of integrated plant protection is the gradual substitution of biological methods for pesticides, regulation of the use of pesticides, and finding chemical agents with selective action [15].

2. CURRENT TRENDS AND FUTURE PERSPECTIVES

In the past, synthetic pesticides have played a major role in crop protection programmes and have immensely benefited mankind. Nevertheless, their indiscriminate use has resulted in the development of resistance by pests (insects, weeds, etc), resurgence and outbreak of new pests, toxicity to non-target organisms and hazardous effects on the environment, thus, endangering the sustainability of ecosystems [16]. An interesting way of searching for bio-rational pesticides is screening naturally occurring compounds in plants [13,14]. Plants, as long-lived stationary organisms, must resist attackers over their lifetime, so they produce and exude constituents of the secondary metabolism (PSMs), playing an important role in their defense mechanisms. In fact, the phytochemicals research has its roots in allelochemistry, involving the complex chemical-mediated interactions between a plant and other organisms in its environment [17]. The concept of bio-control agents (BCAs) has recently been preferred to that of bio-pesticides [18]. Management of plant diseases that was based on chemical control with fumigants and granular nematicides has now given way to resistant cultivars, soil management with organic amendments and crop rotation with resistant or non-host cultivars is also an emerging trend in plant protection [19].

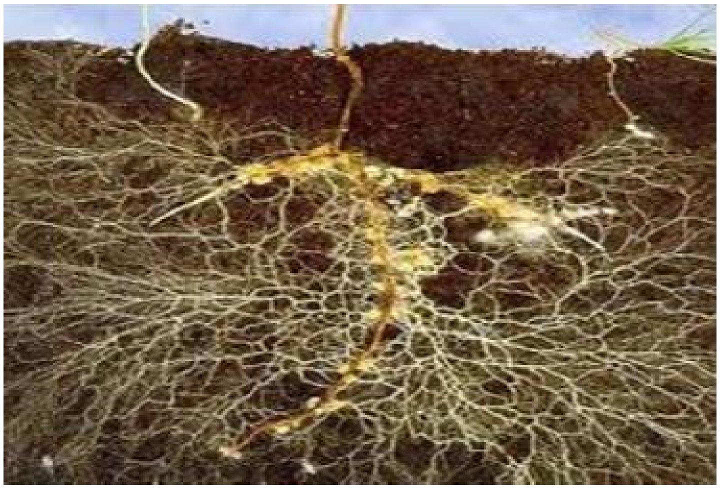


Plate 3. Mycorrhizal network [32]

Flooding of the soil has also been found effective in eliminating root knot nematodes from the soil while ammonia is reported to be toxic to the root knot nematodes, hence, ammonia releasing fertilizers are good for suppression of nematode activity. Slaked lime in combination with chicken manure (organic amendment) has been found to significantly reduce the root-galling index of pepper plants infected with *Meloidogyne incognita* [20]. In the same vein, [21] reported effective control of some pathogens by amendment of potting mixes with composted agro-industrial wastes such as dry cork, dry grape residue (after extraction of juice) and dry rice husk. Soil amendments with some plant extracts have been found to reduce, suppress or even prevent diseases of plants [22,23]. All these constitute effective emerging trends in plant protection that were not there from inception of plant disease control. European Union (EU) has employed a fundamental reform of the Common Agricultural Policy (CAP) highlighting with the respect to the environmental, food safety and animal welfare standards imposing farmlands cross compliance with good agricultural and environmental conditions [24].

This fact has led to the enhancement of nematicides bio-degradation in soil [15,25] and the development of resistance in pests. These facts necessitate the urge for new and alternative pest control methods. PSMs may have applications in weed and pest management, if developed for use as pesticides themselves, or they can be used as model compounds for the development of chemically synthesized derivatives. Many of them are environmentally friendly; pose less risk to humans and animals; have a selective mode of action; avoid the emergence of resistant races of pest species; and as a result, they can be safely used in Integrated Pest Management (IPM) [13]. Furthermore, they may be used as products of choice for organic food production. How to explore the ability of nature and the abundant resources available for plant defense and suitable in pest management for crop protection is the ultimate goal of Plant Protectionists and also an emerging trend indeed. Bio-control agents (BCAs) have long been touted as attractive alternatives to synthetic chemical pesticides for pest management because botanicals reputedly pose little or no threat to the environment and to human health [18]. The body of scientific literature documenting bio-activity of plant derivatives to pests continues to expand rapidly, yet only a handful of botanicals are currently used in agriculture in the industrialized world, and there are few prospects for commercial development of new botanical products [26].

2.1 Bio-control of Pathogens with the Use of Mycorrhizal Biotechnology

The sustainability of bio-control of pathogens with the use of mycorrhiza especially Vesicular Arbuscular Mycorrhiza (VAM) and food security has been studied in Nigeria and seen as an emerging trend. Biotechnology of bio-control in the area of plant-microbe interactions revealing the enzymatic activities of these interactions and the microbial control in plant diseases and their management were extensively researched. The influence of Vesicular-Arbuscular Mycorrhiza (VAM) on disease incidence of some food crops in order to guarantee continuous yield and production of these food crops have also been established [3,27,28,29,30,31].

In the 21st century, emerging trends involve the goals of reducing hunger, starvation and poverty, while at the same time building social and political security. These remain central to any form of development in Africa. Improving agricultural productivity and content of the soils in the sub-saharan Africa has been a major concern for some time now. Continuous cultivation of these soils without adequate soil nutrient replenishment resulted in steady decline of crop productivity and protection [2]. This explains the basis for the introduction of intensification of land-use through a strategy involving proper residue use or tree pruning management with vesicular arbuscular mycorrhiza (VAM) [27].

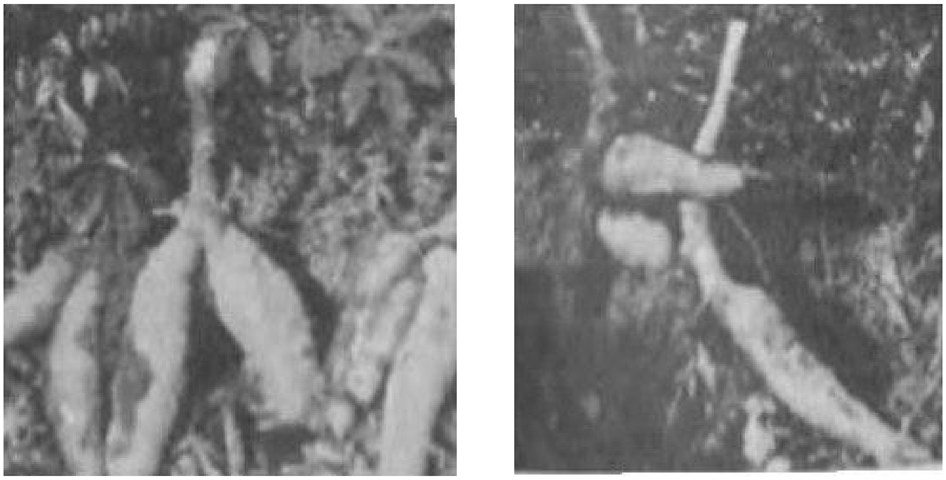
It is also important for food security in Africa given the burgeoning population, the attendant continuous decline in the land area per capita, pathogenic invasions and the inability of resource poor farmers to practice agricultural system with high fertilizer input [33]. The strategy is aimed at generating higher or sustainable yields per unit of land while preserving crop loss from pathogens in Nigeria through the newly emerging agro-biotechnology of mycorrhiza [34]. The biochemical interactions of the arbuscular mycorrhiza-plant-pathogen led to the hypersensitivity reactions which involves the production of secondary metabolites especially enzymes (both extra-cellular and oxidative) and their different levels of activities [35,36]. These in turn lend credence to the induced resistance in plants as well as their significant growth and yield increase on the field [37].

Emerging Bio-control processes involving enzymatic activities in plant-microbe interaction has been demonstrated in Nigeria [38]. The enzymatic mechanisms involved in the ability of mycorrhiza and *Trichoderma* spp in suppressing the pathogenic effect on plants, in order to suppress disease infection was observed. The study reveals the production of cell-wall degrading enzymes in *Glomus etunicatum* (mycorrhiza) association with pepper plant. It confirms the involvement of these enzymes as infectivity factors in the establishment of the association formed. It also further proved the production of cell wall degrading enzymes by *G. etunicatum* through the reduction in plant growth and attainment of chlorotic symptoms at the early stage of mycorrhizal infection. This is a physiological effect that disappeared as soon as the mycorrhiza established itself in the inoculated plants. The results show that arbuscular mycorrhiza (AM) aids maintenance and improvement of soil structure, the uptake of relatively immobile elements; both macronutrients (phosphorus) and micronutrients (zinc), the alleviation of the toxicity of some elements, the interactions with other beneficial soil organisms (nitrogen-fixing rhizobia), and improved protection against pathogens [6,38,39].

Mycorrhizae have also been found to build formidable walls around their roots and also protect them again pathogenic invasion [27,39]. Appraisal of the adoption of an Agro-biotechnology System for Improving Traditional Land-use System in Sub-Saharan Africa by the resource poor farmers in south western Nigeria is another form of emerging trend. This was based on the use of mycorrhiza through training in the process of its propagation. This also showed that VAM inoculation with application of legume-tree mulching can adequately substitute for NPK fertilizer application and plant health as it produced significantly higher tuberous healthy root yield (Plate 4) than uninoculated cassava in alley cropping [40].

Another emerging trend in plant protection is the cultivation and propagation of some of the fungal organisms as well as their bio-remediating abilities. For instance, fungus *Pleurotus pulmonarius* (an edible white rust fungus) has been found to be a potential bio-remediating agent in sites filled with organo-pollutants like crude oil (Fig. 1). Sawdust which can be used to grow this mushroom is being recycled in the process into useful Spent Mushroom Compost (SMC) as agricultural amendment [32].

The mycelium and spent mushroom compost of *Pleurotus pulmonarius* (Plate 5) are useful tools for bioremediation of crude oil polluted soil. The results of the study suggest that a crude oil polluted soil undergoing bioremediation can be bio-stimulated with mycorrhiza fungus. This is in order to enhance crop protection and productivity which can eventually lead to poverty alleviation and then aid food security.



Mycorrhizal cassava tuber **Non-mycorrhizal cassava tuber**

Plate 4. Effects of mycorrhizal inoculation on yield and health of root tubers [40]

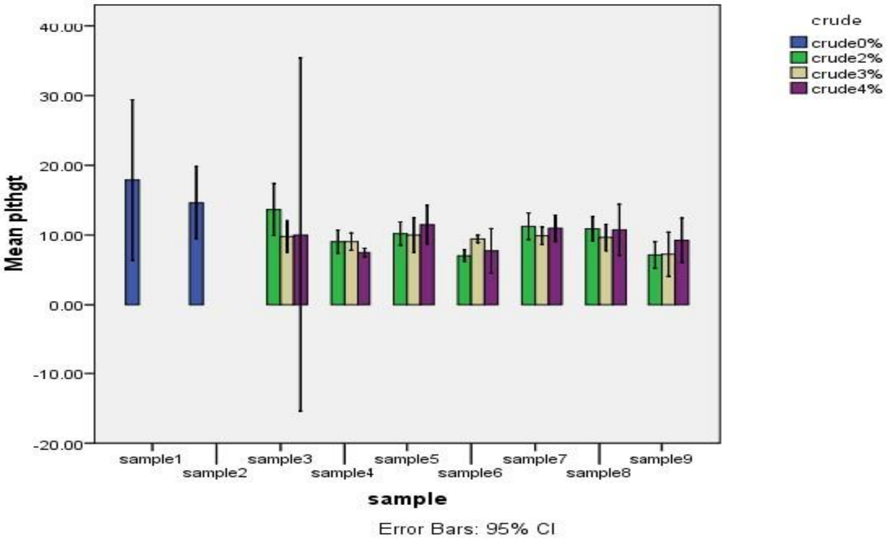


Fig. 1. Mean plant height for different samples at the various concentration of crude [32]

Plate 5. Edible mushroom (*Pleurotus pulmonarius*) [32]

Strains of yeasts (fungi) are effective bio-control agents of fungal pathogens associated with fruit or post-harvest decay [41,42].

2.2 Plant Diseases and How Plants Defend Themselves (Resistance)

2.2.1 Plant defenses

Broadly defined, disease is any physiological abnormality or significant disruption in the ‘normal’ health of a plant. Disease can be caused by living (biotic) agents, including fungi and bacteria, or by environmental (abiotic) factors such as nutrient deficiency, drought, lack of oxygen, excessive temperature, ultraviolet radiation, or pollution. In order to protect themselves from damage, plants have developed a wide variety of constitutive and inducible defenses.

Constitutive (continuous) defenses include many preformed barriers such as cell walls, waxy epidermal cuticles, and bark. These substances not only protect the plant from invasion, they also give the plant strength and rigidity [31]. In addition to preformed barriers, virtually all living plant cells have the ability to detect invading pathogens and respond with inducible defenses including the production of toxic chemicals, pathogen-degrading enzymes, and deliberate cell suicide [43]. Plants often wait until pathogens are detected before producing toxic chemicals or defense-related proteins because of the high energy costs and nutrient requirements associated with their production and maintenance.

Resistant hosts prevent or slow the development and reproduction of the majority of pathogen propagules that they come into contact with. Resistance can be expressed at many stages in the infection process; from inhibition of propagule germination and penetration, to the restriction of colony development after the pathogen has become established [44]. The defence barriers erected by plants are coordinated system of molecular, cellular and tissue-based responses to pathogen attack. Many plants and seeds contain proteins that specifically inhibit pathogen and pest enzymes by forming complexes that block active sites or alter enzyme conformations, ultimately reducing enzyme function. These proteins are generally small and rich in the amino acid cysteine [43]. They include defensins, amylase inhibitors, lectins, and proteinase inhibitors. Unlike simple chemicals such as terpenoids, phenolics, and alkaloids, proteins require a great deal of plant resources and energy to produce; consequently, many defensive proteins are only made in significant quantities after a pathogen or pest has attacked the plant. Once activated, however, defensive proteins and enzymes effectively inhibit fungi, bacteria, nematodes, and insect herbivores.

2.2.1.1 Plant defenses: Passive defenses

Protection from a pathogen's initial invasion is achieved via passive defenses, such as physical and/or chemical barriers.

Physical barriers largely involve properties of the plant surface, that is, the cuticle, stomata and cell walls. Pathogens produce a range of cutin-degrading enzymes, which are often crucial to the successful penetration of the plant tissue. The thickness of the cuticle, the presence of secondary cell wall, and the size of stomatal pores can all affect the success with which a pathogen invades a host. Some plants invest in very thick walls and/or cuticles, and bark (where present) can also provide a physical impediment to infection [1]. The vertical orientation of leaves can also add to plant resistance, by preventing the formation of moisture films of the leaf surfaces, inhibiting infection by pathogens reliant on water for motility.

Chemical barriers include compounds, such as "phytoanticipins", that have antimicrobial activity and compounds that affect the vectors of plant viruses. Phenols and quinones are two classes of antimicrobial compounds produced by some plants. Inhibiting compounds may be excreted into the external environment, accumulate in dead cells or be sequestered into vacuoles in an inactive form. The young fruit of numerous plants (e.g. mangoes, avocado) contain antifungal or antimicrobial compounds that are gradually metabolized during fruit ripening, making unripe fruit less susceptible to disease than ripe fruit. Lactones, cyanogenic glucosides, saponins, terpenoids, stilbenes and tannins are also plant-produced compounds associated with pathogen resistance [44]. Saponins are a class of phytoanticipins that destroy membrane integrity in saponin-sensitive parasites, and which are stored in an inactive form in the vacuoles of the plant cell, becoming active when hydrolase enzymes are released following wounding or infection [1]. Some pathogens are able to release enzymes that detoxify plant saponins, making them insensitive to this line of defense.

Conversely, resistance of some plants to specific pathogens is the result of insensitivity to pathogen-produced host specific toxins [1]. Resistance genes may encode an enzyme that converts the toxin into a non-toxic derivative or the absence of a receptor to the toxin. Another group of defensive compounds are the plant defensins, which interfere with pathogen nutrition and retard their development. Secreted defensins can create an antimicrobial micro-environment for germinating seeds and accumulated defensins can also provide defence against insect-transmitted viruses in flowers, leaves and tubers. There are also proteins, both constitutive and induced, that play important roles in plant defense [45].

2.2.1.2 Plant defenses: Active/ induced defenses pathogen recognition

Plants use a vast array of signals originating from micro-organisms and the environment to recognize pathogens and elicit plant defence responses. Non-specific elicitors of biotic and abiotic origin induce host defences in a broad range of host species. Abiotic elicitors such as heavy metal ions or UV light can induce stress responses in exposed tissues, which may provide an additional barrier to invading pathogens or alternatively, increase the plant's susceptibility to infection [1]. Biotic elicitors include cell wall fragments released from fungi and bacteria [1], hydrolytic enzymes of plant or pathogen origin, some peptides, glycoproteins and polyunsaturated fatty acids. These elicitors induce defence responses in a range of host species. Often, non-specific elicitors act as a general indication that the cell has been damaged in some way (for example, the release of fragments of the host's own cell wall can elicit defence responses) [1].

Specific elicitors enable defence against a very specific pathogen, and are conditioned by avirulence genes in that pathogen. Avirulence genes determine the pathogen's host range, but are only able to function in the presence of another set of genes, the 'hypersensitive response and pathogenicity' (Hrp) gene cluster. Some Hrp gene products are involved in disguising the pathogen from host recognition, thus playing a role in both virulence and avirulence. For a biotroph to form a successful infection, it must establish a basic compatibility with its host. The pathogen may also produce compatibility factors that delay, avoid or negate recognition by a normally resistant host plant [1]. Virulent strains appear to be able to suppress the resistance mechanisms of the host, but are not able to halt resistance responses once they are activated. Incompatibility between a host and a pathogen results in the recognition of the pathogen and activation of defence mechanisms, while compatibility results in infection.

Specific elicitors are encoded by avirulence genes, and these peptides are believed to bind to receptor peptides, encoded by host resistance genes. Recognition of the avirulence gene products by the host triggers signal transduction pathways that cause a massive shift in gene transcription and plant cell metabolism, and local and systemic signals are released that prime the rest of the plant against further infection [1]. The presence of non-specific elicitors, such as the release of host and pathogen wall fragments, during this process may amplify the defence response. Host parasite specific resistance is determined by the interactions between products of pathogen avirulence genes [46], specific elicitors and products of host resistance genes. The defence responses of plants can be very rapid [1]. Host gene expression begins within minutes, or even seconds, of exposure to elicitors or pathogens. A diverse range of elicitors can induce a common set of responses in the host, suggesting that second messengers are involved in the signaling pathway between pathogen attack and host response, hence, rapid active defence induced [1]. This could be at the cell membrane level or even at the cell wall level, as represented in the Plate 6.

The cytoplasmic aggregates are thought to contain cellular apparatus for the synthesis of cell wall fortifications. If the host cell can repair and reinforce its cell walls quickly enough, it might reduce the penetration efficiency of the pathogen [1]. Several types of reinforcement are produced by host cells. A papilla is a deposit of callose, silicon, lignin and proteins between the cell wall and cell membrane, directly below the point of attempted penetration, while lignitubers are lignified callose reinforcements that ensheath invading hyphal tips. These form the structurally induced defences of plant.

2.3 Structural Induced Defenses

- Abscission layer
- Cork layers
- Papillae /callose
- Tyloses
- Lignifications
- Gums and Resins

The ability to repair wounds can help protect the plant from further infection by other, opportunistic pathogens. A secondary meristem in fleshy tissues, fruits, roots and bark, the cork cambium, can produce cork cells, which have thick, suberized walls. These cells can create a barrier to the pathogen and, in some cases, develop an abscission layer around the site of infection, causing the infected tissue to be separated from the healthy tissue. Secretion of protective gums and formation of tyloses are similar examples [1].

Hydroxyproline-rich glycoproteins are structural cell wall proteins involved in secondary cell wall thickening. The expression of genes governing their production is activated ahead of invading hyphae, reinforcing walls. Cross-linking of hydroxyproline-rich glycoproteins caused by the release of hydrogen peroxide in the oxidative burst also reinforces cell wall compartments. Rapid deposition of lignin and suberin following infection also increases resistance to pathogens in many plants [1]. Lignin can also bind to hyphal tips, thus, physically restraining them and restricting the diffusion of their enzymes and toxins into, and the extraction of water and nutrients out of, the host's cell. Cell wall reinforcements tend to be larger and more quickly formed in resistant hosts than in susceptible hosts, and inhibition of the production of callose or lignin synthesis by the pathogen enhances its penetration efficiency [45].

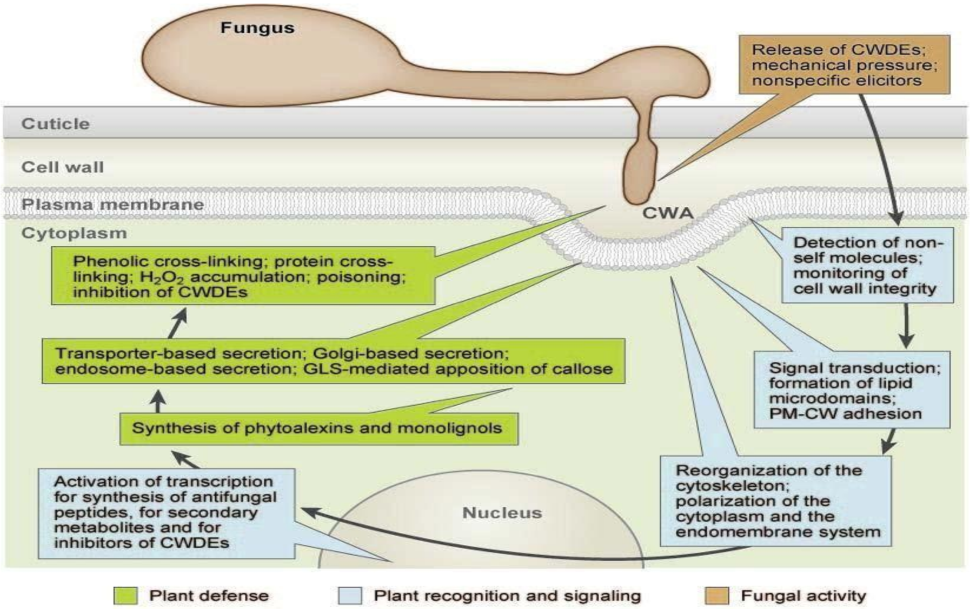


Plate 6. Active defences at the cell membrane and cell wall
(Source: researchgate.net)

Plate 7. The formation of a circular abscission layer causes the infected part to fall out

Plate 8. Papilla (arrow) formed around fungal hypha at the site of attempted infection Lignitubers

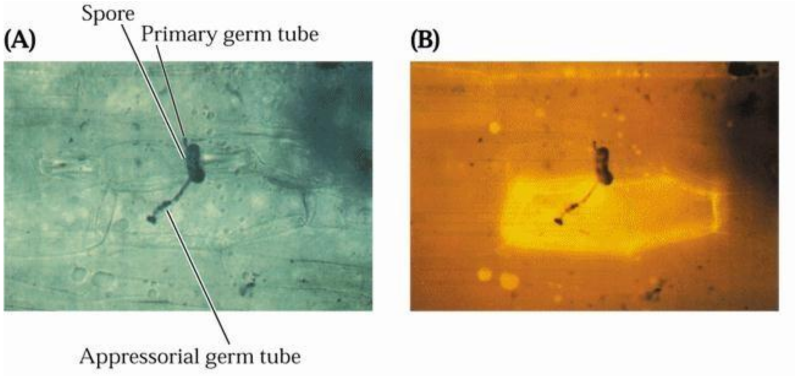


Plate 9. A resistance response localized to pathogen invasion site

2.4 Induced Biochemical Defense the Hypersensitive Response

Pathogens have developed countermeasures that are able to suppress basal resistance in certain plant species. If a pathogen is capable of suppressing basal defense, plants may respond with another line of defense: the hypersensitive response (HR) [1]. Hypersensitive cell death is another widespread mechanism used by hosts to prevent the spread of a pathogen. This is a form of emerging trend that is often associated with the initiation of other responses, such as lignification and the synthesis of anti-microbial compounds for plant defense [47,48]. The HR is characterized by deliberate plant cell suicide at the site of infection. Although drastic compared to basal resistance, the HR may limit pathogen access to water and nutrients by sacrificing a few cells in order to save the rest of the plant. The HR is typically more pathogen-specific than basal resistance and is often triggered when gene products in the plant cell recognize the presence of specific disease-causing effector molecules introduced into the host by the pathogen. Bacteria, fungi, viruses, and microscopic worms called nematodes are capable of inducing the HR in plants. The success of hypersensitive cell death as a resistance mechanism depends on the nutritional requirements of the specific pathogen and the timing, magnitude and location of the host response. Once the hypersensitive response has been triggered, plant tissues may become highly resistant to a broad range of pathogens for an extended period of time. This phenomenon is called systemic acquired resistance (SAR) and represents a heightened state of readiness in which plant resources are mobilized in case of further attack. Researchers have learned to artificially trigger SAR by spraying plants with chemicals called plant activators. These substances are gaining favor in the agricultural community because they are much less toxic to humans and wildlife than fungicides or antibiotics, and their protective effects can last much longer [1].

Plate 10. Hypersensitive response lesion on an *Arabidopsis* leaf [1]

2.5 Antibiotic Compounds- Phytoalexins

Phytoalexins are low molecular weight antibiotics produced by many (but not all) plants in response to infection. There are many biotic elicitors of phytoalexin production, such as cell wall components, as well as abiotic elicitors, such as heavy metals and ultraviolet light. Phytoalexins inhibit the growth of bacteria and fungi *in-vivo* and *in-vitro*, and production of these antibiotics during an infection can induce resistance to subsequent infections by that pathogen. They include pterocarpans, sesquiterpenes, cryptophenols, isocoumarins, isoflavenoids, and others. Phytoalexins may be produced by any part of the plant, although different phytoalexins can accumulate in different organs. Generally, related plant species produce structurally-related phytoalexins, and many produce more than one, enabling the plant to present a toxic cocktail to invading pathogens. Phytoalexins are produced in cells surrounding an infection site and delivered to the infected cell packaged in lipid vesicles, creating a toxic micro-environment in the infected cell and, hopefully, preventing disease establishment. Phytoalexin accumulation is often associated with hypersensitive cell death, although only living cells can synthesize phytoalexins. Some plants can also sequester phytoalexins into vacuoles as stores of inactive sugar-conjugates, which can be cleaved and released quickly if initial defence responses are unsuccessful. Examples of phytoalexins include **medicarpin** produced by alfalfa (*Medicago sativa*), **rishitin** produced by both tomatoes and potatoes (the *Solanaceae* family), and **camalexin**, produced by *Arabidopsis thaliana* [1].

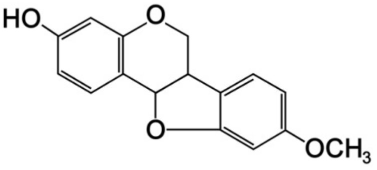


Plate 11. Medicarpin, a phytoalexin

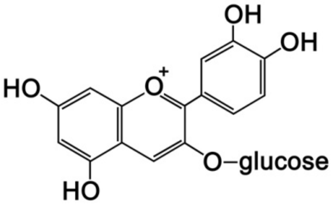


Plate12. Cyanin glycoside, an anthocyanin

Protein synthesis in response to a pathogen is a novel response to infection, many of which have beta-glucanase, chitinase or lysozyme activity. Some pathogenesis-related proteins disrupt pathogen nutrition. The presence of low levels of these proteins in healthy plants suggests that they might have other roles in plant growth and development aside from disease resistance. Chitinase and glucanase accumulate in the vacuoles, and glucanase is also sometimes secreted into the intercellular space [1]. They dissolve the fungal cell wall, fragments of which then elicit hypersensitive cell death. The breakdown of the vacuole during decompartmentalisation of the cytoplasm results in a flood of hydrolytic enzymes, which have antiviral, antifungal and antibacterial activity. The accumulation of pathogenesis-related proteins peaks around 7-10 days after initial infection. The presence of these proteins before infection increases the plant's resistance to pathogens, as in the case of systemic acquired resistance.

2.6 Systemic Acquired Resistance

Systemic acquired resistance, or induced resistance, is characterized by the increased resistance of a plant to a wide range of pathogens following infection by one pathogen.

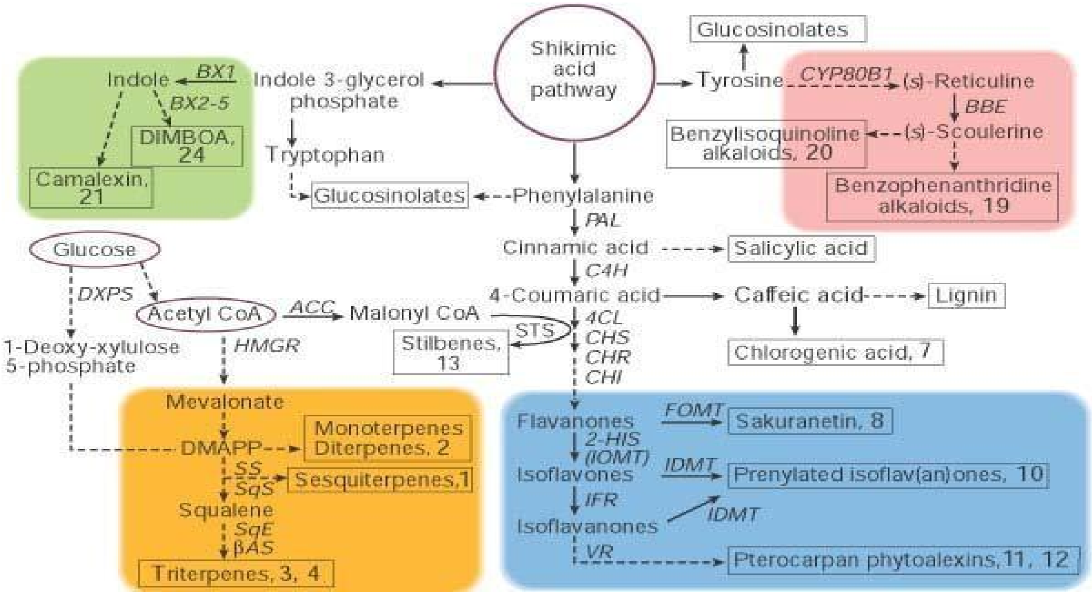


Plate 13. Biosynthesis of phytoalexins

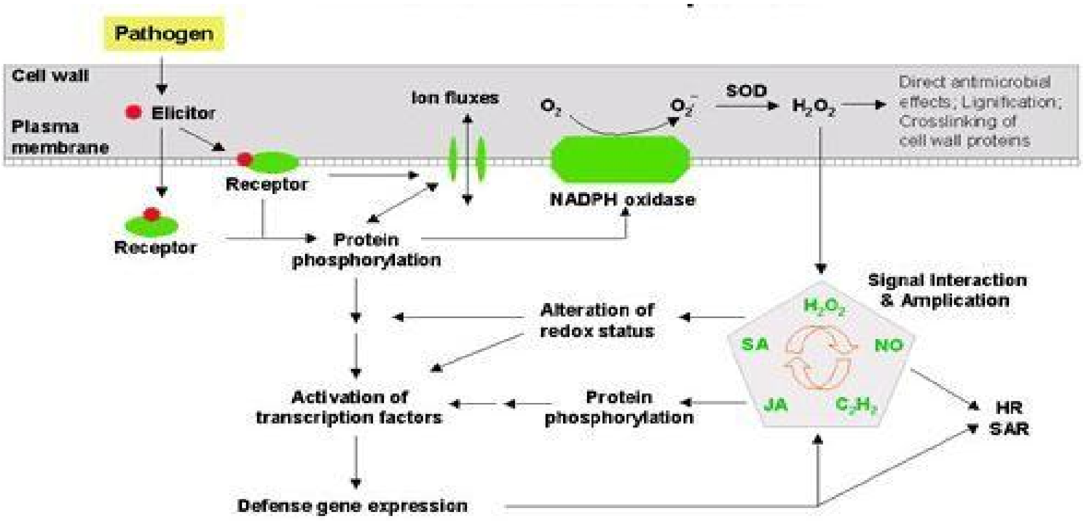


Plate 14. A simplified model for signal transduction in plant defense responses

It is the resistance acquired by the plant during its life time (It could be induced systemic or local resistance). The inducer elicits responses from the host plant and then triggers some sleeping resistance genes that will make it (the host plant) active [1]. The specific interaction between host and pathogen is very crucial to the success of the plant's resistance or the pathogen's invasion, and is mediated by the many pathways involved in producing or detecting elicitors, enhancers, suppressors and secondary signals [49,50]. However, plant disease resistance can also be induced in specific plant cultivars within the host range, or only in response to specific races of pathogen.

3. CONCLUSION

Generally, emerging trend in plant protection stems from the strengthening of the old control methods to microbial control of pathogens. This is based on the beneficial interactions of microbes on plant's health, the mechanisms of which include: pathogen suppression by microbial agents that could be through competition with the pathogen itself; antagonism in form of antibiosis, parasitism and then, predation. It could also be through probiotic action, which is plant growth production, elicitation of defense responses and induction of systemic acquired resistance or suppression of toxin production by the pathogen. Emerging trends can also be viewed from the impact of environmental conditions on plant's resistance (whether constitutive or induced), integrated pest management strategies, biological control, cultural. Indirect destruction of propagules or active growth of pathogens in soil can also be achieved by bio-fumigation (release of volatile compounds that could be antifungal, antibacterial and anti-nematode into the soil) or myco-fumigation (in which specific fungi produce volatiles that kill or inhibit the pathogens without direct contact with the pathogen). The current trend in plant protection also involves constitutive and induced defenses by plant (as enumerated above) and plant immunity (i.e. R-Genes). Future perspective is that scientists have recently developed means of employing the inherent defence mechanisms present in plants to evolve new methods of protection against pests. Transgenic plants have been developed and are currently subjects of debates regarding their acceptability in most countries, especially Africa. The products from these new methods of protecting plants against pests and diseases have been commercialized by multi-national companies to the detriment of developing countries.

Conclusively, the numerous examples of plant secondary metabolites (phytoalexins and phytoanticipins) reviewed here demonstrate that they constitute an important mechanism to stop the spread of phytopathogens in plants, both by acting as antimicrobials themselves or as elicitors of other defence responses. More interestingly, phytoalexins and phytoanticipins have been found to be active against pathogens and their use as "antibiotic potentiators" or "virulence attenuators" for the control of infectious diseases is promising. Hence, the progressing threat of pathogens leading to crop losses, food insecurity; attenuated poverty and the incessant need for crop protection, strengthen the importance of the research activities aimed at the isolation and characterization of plant secondary metabolites and the understanding of the mechanisms involved in the natural defences of plants against microbial [51,52]. Importance of strengthening the plant host to resist attack of pathogens has since been recognized even by the farmers. This they do in the traditional agriculture by storing seeds from vigorous and healthy looking crops, hence, resistance to disease and pests is a naturally occurring phenomenon in plants. They are now with better understanding and where withal, becoming effective tools especially in the hands of the protectionists. As these tools, from the naturally inherent plant constituents to the genetically based defences are been passed from the protectionists to the breeders, thus, creating resistant cultivar that can withstand different conditions, leading to sustainable food security. The main advantage of plant amendments is that they may be easily and cheaply produced by farmers and small scale industries as chopped leaf and stem, powder or partially purified extracts. Application of plant materials to soil is an inexpensive and effective technique and its easy adaptability will give additional advantages leading to acceptance of this technology by farmers.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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