Plant immune systems as pests and diseases mitigation

D Purnomo
Department of Agrotechnology, Faculty of Agriculture, Universitas Sebelas Maret, Jl. Ir. Sutami 36 A, Kentingan, Surakarta, 57126 Indonesia
Corresponding author: djokopurnomo@staff.uns.ac.id

Abstract. The phenomenon of climate change, which is currently still in the form of a weather anomaly, has disrupted the agricultural system. Increasing temperatures and changing rain patterns have resulted in several disasters such as heatwaves, strong winds (typhoons), and floods. For plants, these conditions result in disruption of plant growth and response to herbivores and pathogens. Plants have a mechanism of resistance to pests and pathogens intrinsically and extrinsically through growth, special morphology, metabolism of certain compounds such as volatiles (becoming disliked by herbivores or inviting natural enemies), and secondary metabolites. Secondary metabolites protect plants from pests (herbivores) and infection by disease microbes through mechanisms at the structural and metabolic levels. The level of the herbivore structure cannot penetrate, preventing mechanical damage. Secondary metabolites by inducing the synthesis of antibiotics derived from phenolics and terpenoids (phytoalexin). Antibiotics affect herbivores by suppressing growth, development, reproduction, to death. Secondary metabolites are typical of a plant as anti-insect, anti-fungal, anti-bacterial, and anti-viral compounds. Engineering to increase plant immunity against pests and pathogens by increasing secondary metabolites, cultivation, and genetic potential is developed. This program is not only related to environmentally friendly crop cultivation but also to anticipate climate change.

1. Introduction
The impacts of climate change on agricultural systems threaten crop production with important implications for food security. Since the 1950s, the agricultural system has undergone systematic differences due to climatic conditions. Climate change occurs in an increase in the earth’s surface temperature, average rainfall, more significant weather variability, and extreme weather conditions (i.e., heatwaves, drought, bush fires, hurricanes, floods). In Indonesia, there has been an increase in the average temperature of 0.7°C throughout the 1981-2020 period, and the number of days with temperatures above 33°C has increased in the last three years [1]. An increase in temperature of 1°C results in a decrease in primary grain yields of between 2.5 and 16% in tropical and subtropical areas [2]. This is because of temperature affects plant growth and plant response to pests and pathogens [3]. Abiotic stress can have a positive or negative effect on plant defenses. Temperature, water, relative humidity significantly affect plant resistance and pathogen invasion. Higher temperatures promote the development of certain pests and can shorten the harvest cycle [4]. In addition, an increase in temperature affects the distribution and viability of plant viruses and their vectors [3], [5]. High temperatures affecting host resistance to pathogens have been reported in tobacco infected with the tobacco mosaic virus [6]. Climatic conditions with a diversity of pests and plant diseases are closely related, referring to the biodiversity in the tropics [7]–[9] is higher than in sub-tropical areas [10] as a result of high temperature and humidity [11].
Disruption to crops, mainly by pests and diseases, threatens food security nationally, regionally, and globally. The yield loss of rice (Oryza sativa), maize (Zea mays), and soybean (Glycine max) in Indonesia due to pests and diseases is 20-30% [12], 50% [13], and 80% [14] respectively in once planted. Internationally, the estimated loss of agricultural products due to pests (viruses, bacteria, fungi, nematodes, and insects) is 30% annually [15], and the incidence is constant. Losses due to a type of pest can occur widely between countries because these pests have a wide distribution, migrating from one region to another according to climatic conditions. An example is a brown planthopper (Nilaparvata lugens) in China, migration originates from Indochina in the spring and summer [16].

The population of Indonesia has reached 270.20 million in 2020, an increase of 32.56 million compared to 2010 [17]. This causes the need for food to increase along with population’s rise. Based on the rice consumption per capita of 111.58 kg, the demand for rice will reach 30.15 million tons. In 2020, rice production will get 31.63 million tons, bringing a surplus of 1.63 million. However, following economic growth and increased consumption, increased food production is needed [18]. Efforts to increase production anticipate an increase in population to achieve food security. In this case, the above efforts face enormous pressure related to climate change, so it becomes a challenge in implementing the mitigation approach. Efforts to increase production must continue to be carried out either intensively or extensively, maintaining optimum environmental conditions (water, soil, and nutrition), stopping the rate of land conversion (especially rice fields), food diversity, including decreasing yield losses mainly due to pests and diseases.

Plants do not have the opportunity to get out of this condition (impacts of climate change) and must respond and adapt [19], [20], one with the immune system [21]. The immune system allows plants to resist infections of a wide variety of macro (pests) and microorganisms (fungi, bacteria, and viruses). The plant immune response is closely controlled to ensure adequate defense against pathogens while minimizing negative impacts on plant growth [22]. Plants are immune to invading organisms through intrinsic and extrinsic mechanisms. Innate immunity comes from genetic traits, while extrinsic immunity is also called ecological immunity, which occurs due to environmental conditions (strengthening plant growth or weakening invaders) [23], [24]. Based on this understanding, ecological immunity is called pseudo resistance. Intrinsic plant immunity through the mechanism of antixenosis, pests, or diseases do not like or reject. This is because plants contain allelochemicals (chemical antixenosis) or have specific organs (morphological antixenosis). This article reviews the plant's immune system mainly through secondary metabolites in fighting herbivores and pathogens due to climate change.

2. Immune, resistant and tolerant

Plant resistance to pests and diseases is a natural phenomenon based on the mechanism of the immune system. The immune system serves to alert organisms to the presence of pests or pathogens. The disease develops when pathogens can penetrate the layer of the host defense. The immune system differentiates between self and nonself with the first line of defense in plants provided by pattern recognition receptors (PRRs), which recognize harmful microbial- or molecular patterns (MAMP and DAMP) and trigger immune signaling [25]. Plant pattern recognition receptors (PRRs) are transmembrane receptors and produce MAMP-induced immunity. Pathogens are microorganisms and viruses capable of suppressing PRR-based defenses, and then the pathogens will spread various virulence determining effectors to susceptible hosts [26].

The introduction of pathogens in plants results in growth inhibition accompanied by a hypersensitivity response (HR). Hypersensitivity response is programmed cell death, including cytoplasmic shrinkage, chromatin condensation, mitochondrial swelling, vacuolization, and chloroplast disruption. Chloroplasts have an essential role in the defense response in plant HR. First, it is a source of molecules in boosting defense systems such as reactive oxygen species (ROS), reactive nitrogen oxides (NOD) intermediates and salicylic acid (SA), and jasmonic acid (JA) defense hormones. Second, in most cases, light is needed for HR development. Third, some pathogenic effectors have chloroplast localization signals, and in some cases, have been shown to suppress immunity [27].
Plant defense strategies against pests and diseases are resistance and tolerance [28]. Resistance occurs when the structural or chemical properties deter pests and pathogens and thus minimize the amount of damage. Plants can have high, medium, or low resistance. Tolerance occurs when crops reduce the adverse effects of pest and disease damage on crop yields. In addition, plants can be immune or immune as a form of complete resistance to a pathogen (plants are completely undisturbed). Meanwhile, plants that are tolerant despite the disturbance of pests and pathogens, the plants do not experience economic losses. Plants with a perfect tolerance level will achieve the same suitability either damaged or undamaged [29]. Even though the plant was damaged (wound), it soon returned to normal. This occurs because of the strength of the plant habitus, and the damage will immediately recover, the increase in the growth of branches or leaves, the nutritional content of the plant, the efficiency of pests in utilizing plants as nutrients, and compensation for neighboring plants. For example, maize is attacked by root beetles (Diabrotica virgifera), but is almost undisturbed because of the large and dense root volume [30].

Plant resistance and tolerance to pests and diseases were positively correlated with plant nutrient content. Plants that experience nutritional stress will be more susceptible to pests and diseases, while plants with sufficient nutrition will be more tolerant or resistant to pests and diseases. Nutrients can affect plant resistance or tolerance or pathogen virulence. For example, silica (Si) in the cell walls of the epidermis acts as a mechanical barrier for penetration of the stylet and mandibles of sucking and biting insects [31]–[33]. In addition, dissolved Si facilitates rapid deposition of phenolics or phytoalexins at the site of infection and can also form complex phenolics, thereby increasing synthesis and mobility in the apoplast [34], [35]. Potassium content increases the host plant's resistance to obligate and facultative parasites because it increases the synthesis of compounds such as protein, starch, and cellulose. This results in the accumulation of low molecular weight organic compounds that serve as readily available nutrient sources for parasites [36][37].

Compensation for neighboring crops shows high stability in high diversity crops such as yards or forests. High diversity plants synergize with each other; one plant becomes the host of natural enemies for other plant pests [38]. High diversity per crop can provide a regulatory pathway to regulate pest populations and reduce damage and losses. This regulatory network results from complex biotic and abiotic interaction components, enabling endogenous regulation of several potential pest species [39]. Plantations with high diversity can change the regulation of plant pests by modifying development, reproduction, and foraging behavior [40]. Tree strata can also act as a barrier to the spread of pests or act as a diluting element, reducing the density of the host plant [41].

Based on the discussion above, plants inhibit pest attack through the following mechanisms: 1. Antibiosis, affecting or damaging the pest life cycle. Resistance occurs after insects arrive and start using plants as life support. Plant antibiotic substances affect the growth, development, reproduction, and survival of pests. 2. Antixenosis, plants avoid pests because they are not used as food, egg-laying media, or insect habitat. Plants may still suffer damage if the pest does not find alternatives. Antixenosis resistance resulted in a reduction in the number of initial colonization and the population size compared to susceptible plants [42]. 3. Tolerant, the resistance of plants to pests by continuing to grow and produce even though they are attacked, does not affect the pest population. Meanwhile, antibiosis and antixenosis affect the pest population [43].

2.1. Secondary metabolites and resistance
Plants produce organic compounds with low molecular weight consisting of three general groups: primary metabolites directly needed for plant growth, secondary metabolites that mediate plant-environment interactions, and hormones that regulate the organism's metabolism processes. Secondary metabolites are integrated components of metabolic networks that can dynamically act to respond to abiotic and biotic stresses [44]. The reaction of plants to stress is not similar, a secondary metabolite may not present in all plants (only in one or a group of species). In contrast to primary metabolites (amino acids, nucleotides, sugars, lipids), secondary metabolites are a byproduct or intermediate for a synthesis [45].
Secondary metabolite biosynthesis starting from primary pathways such as the glycolysis pathway or shikimate acid then diversifies depending on the type of cell, stage of development, and environment [46]. These compounds are widely distributed in the cells, tissues, and organs of plants. Based on the biosynthetic pathway, secondary metabolites consist of three groups, namely compounds containing nitrogen (cyanogenic glycosides, alkaloids, and glucosinolates), phenolic compounds (flavonoids and phenylpropanoids), and terpenes (isoprenoids) [47]. The shikimate acid pathway produces phenolics which play a role in plant defense mechanisms. Phenolic compounds exhibit antimicrobial and antioxidant properties that help plants avoid pathogenic infections and protect major tissues from the effects of reactive oxygen species [48], and protect plants from herbivorous insects [49]. Terpenoids are also a core component of chemical defense against pests and pathogens [11]. Terpenoids have 5-C isoterpenoids as a basic unit that is toxic and inhibits herbivores. For example, terpenoids can act as protectors of conifers (Pinophyta) in deterring bark beetles, weevils, and fungi [50]. Secondary metabolites with nitrogen and sulfur content also play a role in plant defense against pathogens because they contain compounds produced by amino acid synthesis [51]. Secondary metabolites containing N and S are influenced by the optimum supply of N and S, which increases the ability of plants to cope with different environmental stresses.

Secondary metabolites protect plants from pests (herbivores) and infection by disease microbes through mechanisms at the structural and metabolic levels [52]. At the structural level, the cell wall comprises phenyl propanoic as the main component of lignin and suberin. The bark, cuticle, and wax are protective; herbivores cannot penetrate, thus preventing mechanical damage. If this first line of defense can be passed, another defense mechanism will take effect (antibiotics or enzymes). The production of secondary metabolites can induce the synthesis of phenolic and terpenoid antibiotics to interfere with the nervous system of pests. Antibiotics affect herbivores by suppressing growth, development, reproduction, to death. Invertebrates, several small molecules of neurotransmitters are known to modulate neuroreceptor activity [53].

2.2. Secondary metabolites and herbivores
Antixenosis is a secondary plant metabolite that plays a role in blocking insect colonization or being a deterrent to coming. The orientation of insects to plants includes, among others, food, a place to lay eggs, and take shelter. Plants showing resistance with antixenotic properties were able to reduce the initial number of colonization in one season and reduced population size in each generation compared to susceptible plants. Secondary metabolites to fight against microbial and insect attack (phytoalexins) or stored in inactive form (phytoanticipins). One example of antixenosis is the glucozinolate content which gives a distinctive smell and taste to the Brassicaceae family vegetables, which are not favored by pests [54].

Antibiosis is resistance after the insects colonize a plant. Plants contain antibiotics; when insects eat plants, antibiotics interfere with insects' growth, development, reproduction, and survival. Secondary metabolites of coumarin and tannins make plants unpopular with herbivores, phenylpropanoid as a compound between lignin and suberin synthesis, strengthening cell walls [55]. Alkaloids can modulate nerve signal transduction, namely disrupting ion channels, neurotransmitter receptors so that they can change the physiology and behavior of herbivores [56]. Antibiosis can also make it easier for natural enemies to recognize insects.

2.3. Secondary metabolites and fungi
Most of the plants have secondary antifungal metabolites [57], [58] in the form of phenolics and flavonoids. These compounds are found in fruit and leaf peels with high concentrations that play a role in defense against pigmentation, UV resistance, and disease resistance [59]. Most of the phenolic potential as antioxidants, some of which can chelate heavy metal ions. Phenolic phytoalexins exhibit antibiotic and antifungal activity. Volatile and nonvolatile secondary metabolites have the potential to inhibit pathogenic microorganisms. The effectiveness of the two metabolites on pathogen control differed among pathogens. The nonvolatile secondary metabolite Trichoderma sp. Inhibited the growth
of 25.58% against Colletotrichum sp. and 13.03% against Fusarium oxysporum. Meanwhile, volatile secondary metabolites inhibit Colletotrichum sp. 41.11% and Fusarium oxysporum 12.45% [60]. Phenolic compounds produced by oil palm roots infected with Fusarium oxysporum help plants become resistant to vascular wilt disease [61].

2.4. Secondary Metabolites and Viruses
Secondary metabolites are essential for plant survival against viral pathogens [62]. Some cases, including phenylalanine ammonia-lyases (ZmPALs) in salicylic acid accumulation in maize, can limit virus accumulation, reduce symptom severity and make corn resistant to sugarcane mosaic virus (SCMV), which causes dwarf maize [63]. This occurs because salicylic acid plays an essential role in plant defense against pathogens and abiotic stress [64]. Salicylic acid is synthesized through the phenylpropanoid pathway. The phenylpropanoid pathway is also involved in the biosynthesis of many plant defense compounds, including flavonoids, lignins, tannins, hydroxycinnamic acid, coumarins, etc. stilbenes [49]. The decrease in flavonoids, phytoalexin, and SA in OsPAL6-knockout mutant rice plants caused susceptibility to Magnaporthe oryzae [65]. Secondary metabolites phenolite, scopoletin and lignin, can activate the defense response in tobacco BY-2 cell suspension and protect tobacco from TMV [66].

2.5. Secondary metabolites and bacteria
Plant secondary metabolites released by the roots function as antimicrobial and antibacterial. Maize produces sesquiterpenes and releases sesquiterpene (E) -β-caryophyllene in the rhizosphere when attacked by Pantoaea stewartii subsp. Potatoes have terpenoids when attacked by Clavibacter michiganensis subsp. Sepedonicus. Plants release a wide variety of secondary metabolites through their roots as a form of defense against herbivores, pests, and pathogens [67]. The state of protection in tobacco plants increases alkaloid production after stimulation from the Pseudomonas solanacearum bacteria. In addition, nicotine and nornicotine increased by 220%. The attack by the bacteria only causes a small portion of mechanical damage. Alkaloids are synthesized in the roots and then transported to the top of the plant [68].

2.6. Elicitor
Plants fight pathogens (fungi, viruses, insects, nematodes) and environmental stress (drought, salinity, temperature, exposure to UV radiation) through receptor and sensor signals and activate defense responses to stabilize pressure. One response is the accumulation of secondary metabolites. Secondary metabolite synthesis can be increased through elicitation with biotic elicitors (protein, carbohydrates, plant growth-promoting rhizobacteria, fungi, hormones) and abiotic (heavy metals, low and high temperatures, light, salt, dryness) [69].

Elicitors generally refer to agents that stimulate a plant's defense response. Biotic elicitors, especially those derived from fungi such as arbuscular mycorrhizae, Piriformospora indica, are known to increase the production of secondary metabolites of alkaloids, terpenoids, and steroids [70]. Elicitor of fungal cell extract increases the production of secondary metabolites in plant cell suspension cultures [70]– [72]. Apart from chemical agents, UV radiation, hyperosmotic stress, changes in temperature, and light intensity be effective at increasing secondary metabolites in some plant species. Chemical elicitors such as salicylic acid, methyl salicylic, benzoic acid, chitosan can affect the production of phenolic compounds and the activation of various enzymes related to plant defense [73], [74]. In addition, elicitor-induced stress results in the activation of several genes related to defense or inactivation of genes not related to defense, transient phosphorylation/deposition of proteins, the expression of enzymes whose information can be used to ascertain the biosynthetic pathways of secondary metabolites [75].

3. Conclusion
Efforts that can be made to control pests and diseases by plants are secondary metabolites through mechanisms at the structural and metabolic levels. Secondary metabolites are anti-insect, anti-fungal,
anti-bacterial, and anti-viral compounds. Engineering to increase plant immunity against pests and pathogens by increasing the production of secondary metabolites with elicitors. This program is not only related to environmentally friendly crop cultivation but also to anticipate climate change.

References

[1] BMKG (Indonesian Agency for Meteorology, Climatology and Geophysics) 2021 Buletin Hujan Bulanan di Indonesia No 4 pp 1–29 [Online] Available: https://www.bmkg.go.id/berita/?p=buletin-hujan-bulan-di-indonesia-updated-april-2021&lang=ID&tag=buletin-iklim

[2] Akinseye F M, Ajeigbe H A, Traore P C S, Agele S O, Zemadim B and Whitbread A 2019 Improving sorghum productivity under changing climatic conditions: A modelling approach F. Crop. Res. 246 107685

[3] Dossa G et al 2020 Rice pyramided line IRBB67 (Xa4 / Xa7) homeostasis under combined stress of high temperature and bacterial blight Sci. Rep. 67(10) 1–15

[4] Sharma A and Anandhi A 2020 Temperature based indicators to develop adaptive responses for crop production in Florida, USA Ecol. Indic. 121 107064

[5] Katsaruware-chapoto R D, Mafongoya P L and Gubba A 2017 Responses of Insect Pests and Plant Diseases to Changing and Variable Climate: A Review J. Agric. Sci. 9(12) 160–168

[6] Aradottir G I and Crespo-herrera L 2021 Host plant resistance in wheat to barley yellow dwarf viruses and their aphid vectors: a review Curr. Opin. Insect Sci. 45 59–68

[7] Nurvianto S, Yudha R P and Sugito Y S 2021 Impact of logging on the biodiversity and composition of flora and fauna in the mangrove forests of Bintuni Bay, West Papua, Indonesia For. Ecol. Manage. 488 119038

[8] Koh L P and Kettle C J 2010 Biodiversity State and Trends in Southeast Asia Vol. 1 (Netherland: Elsevier Ltd.)

[9] Kment P et al 2019 Insect trypanosomatids in Papua New Guinea: high endemism and diversity Int. J. Parasitol. 49 1075–1086

[10] Mugerwa H et al 2021 Genetic diversity of whitefly (Bemisia spp.) on crop and uncultivated plants in Uganda: implications for the control of this devastating pest species complex in Africa J. Pest Sci. 2004 0123456789

[11] Ye J, Zhang L, Zhang X, Wu X and Fang R 2020 Plant Defense Networks against Insect-Borne Pathogens Trends Plant Sci. 26(3) 272–287

[12] Wiyono S, Istiaji B, Triwidodo H and Suryaningsih A S 2020 Abundance of soil microbes, endophytic fungi and blast disease of paddy rice with three pest management practices Biodiversitas 21(9) 4234–4239

[13] Herlinda S, Octariati N and Suwandi S 2020 Exploring entomopathogenic fungi from South Sumatra (Indonesia) soil and their pathogenicity against a new invasive maize pest, Spodoptera frugiperda Biodiversitas 21(7) 2955–2965

[14] Erdiansyah I, Syarief M and Taufika R 2021 Virulence of Spodoptera Litura Nuclear Polyhedrosis Virus (SLNPV) with kaolin as carrier material on spodoptera litura and tetragonula laeviceps on soybean IOP Conf. Ser. Earth Environ. Sci. 672 012097

[15] Jang Y, Park J and Kim K 2020 Antimicrobial Activity of Chrysoserial 7 and Chochlioquinone 9, White-Backed Planthopper-Resistant Compounds, Against Rice Pathogenic Strains,” Biology (Basel). 382(9) 1–15

[16] Hu G et al 2019 Long-term seasonal forecasting of a major migrant insect pest: the brown planthopper in the Lower Yangtze River Valley J. Pest Sci. 92(2) 417–428

[17] BPS (Central Bureau of Statistics) 2020 Total Population of Indonesia [Online] Available: https://www.bps.go.id/

[18] Pateiro L, Lago X, Doval M I and Gandara J 2020 Toward a sustainable metric and indicators for the goal of sustainability in agricultural and food production Crit. Rev. Food Sci. Nutr. 0(0) 1–22
[19] Pérez-Girón C J, Álvarez-Álvarez P, Díaz-Varela E R and Mendes Lopes D M 2020 Influence of climate variations on primary production indicators and on the resilience of forest ecosystems in a future scenario of climate change: Application to sweet chestnut agroforestry systems in the Iberian Peninsula 

[20] Mosquera-Losada M R et al 2018 Agroforestry in Europe: A land management policy tool to combat climate change 

[21] Katagiri F and Tsuda K 2010 Understanding the Plant Immune System 

[22] Hua J 2013 Modulation of plant immunity by light, circadian rhythm and temperature 

[23] Wang W, Li P, Dang P, Zhao S, Lai D and Zhou L 2018 Rice Secondary Metabolites: Structures, Roles, Biosynthesis, and Metabolic Regulation 

[24] Bentham A R et al 2020 A molecular roadmap to the plant immune system 

[25] Coll N S, Epple P and Dangl J L 2011 Programmed cell death in the plant immune system 

[26] Swartzwelter B J et al 2020 The Impact of Nanoparticles on Innate Immune Activation by Live Bacteria 

[27] Prigozhin D M and Krasileva K 2021 Analysis of intraspecies diversity reveals a subset of highly variable plant immune receptors and predicts their binding sites 

[28] Fornoni J and Valverde P L 2007 The Evolution of Resistance and Tolerance to Herbivores,” 

[29] Lin P, Paudel S, Afzal A, Shedd N L and Felton G W 2020 Changes in tolerance and resistance of a plant to insect herbivores under variable water availability 

[30] Krawczyk K, Fory J and Bere P K 2020 Transmission of Pantoea ananatis, the causal agent of leaf spot disease of maize (Zea mays) by western corn rootworm (Diabrotica virgifera LeConte) 

[31] Roy S and Panda S 2020 Effect of Silicon Amendments in Enhancing Resistance of Rice Plants against Brown Plant Hopper Nilaparvata lugens (Stal.) in Odisha 

[32] Van Bruggen A H C, Goss E M, Havelaar A, Van Diepeningen A D, Finckh M R and Morris J G 2019 One Health - Cycling of diverse microbial communities as a connecting force for soil, plant, animal, human and ecosystem health 

[33] Yang L, Han Y, Li P, Wen L and Hou M 2017 Silicon amendment to rice plants impairs sucking behaviors and population growth in the phloem feeder Nilaparvata lugens (Hemiptera: Delphacidae) 

[34] Kunej U, Mikulić M, Radišek S and Stajner N 2020 Changes in the Phenolic Compounds of Hop (Humulus lupulus L.) Induced by Infection with Verticillium nonalfalfae, the Causal Agent of Hop Plants 

[35] Fortunato A A, Luís W and Rodrigues F A 2014 Biochemistry and Cell Biology Phenylpropanoid Pathway Is Potentiated by Silicon in the Roots of Banana Plants During the Infection Process of Fusarium oxysporum f. sp. cubense 

[36] Tippe D E et al 2020 Fertilisers differentially affect facultative and obligate parasitic weeds of rice and only occasionally improve yields in infested fields 

[37] Lu H et al 2018 Resistance of rice to insect pests mediated by suppression of serotonin biosynthesis,” 

[38] Ratnadass A, Fernandes P, Avelino J and Habib R 2012 Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: a review 

[39] Bagny L, Roudine S, Daout D and Carval D 2019 Pest-regulating networks of the coffee berry borer (Hypothenemus hampei) in agroforestry systems 


[40] Keesing F et al. 2010 Impacts of biodiversity on the emergence and transmission of infectious diseases Nature 468 647–652
[41] Bieng M N, Akoutou E, Eunice M, Danie G and Nomo L B 2017 Assessment of the interaction between the spatial organization of citrus trees populations in cocoa agroforests and Phytophthora root rot disease of citrus severity Agrofor. Syst. 93 493–502
[42] Hondelmann P, Paul C, Schreiner M and Meyhofer R 2020 Importance of Antixenosis and Antibiosis Resistance to the Cabbage Whitefly (Aleyrodes proletella) in Brussels Sprout Cultivars Insects 56(11) 1–16
[43] Bueno N et al. 2020 Characterization of Antixenosis and Antibiosis of Corn Genotypes to Dichelops melacanthus Dallas (Hemiptera: Pentatomidae) Gesunde Pflanz. 73 67–76
[44] Erb M and Kliebenstein D J 2020 Plant Secondary Metabolites as Defenses, Regulators, and Primary Metabolites: The Blurred Plant Physiol. 184 39–52
[45] Mhlongo M I, Piater L A, Steenkamp P A, Labuschagne N and Dubery I A 2020 Metabolic Profiling of PGPR-Treated Tomato Plants Reveal Priming-Related Adaptations of Secondary Metabolites and Aromatic Amino Acids Metabolites 210 10
[46] Olioto T, Federal U, Maria D S, Nardino M, Carvalho I R and De Pelotas U F 2017 Plant secondary metabolites and its dynamical systems of induction in response to environmental factors: A review African J. Agric. Res. 12(2) 71–84
[47] Balestrini R et al. 2021 Strategies to Modulate Specialized Metabolism in Mediterranean Crops: From Molecular Aspects to Field Int. J. Mol. Sci. 28872
[48] Choudhary P, Rani P, Rana S, Nagarathnam R and Muthamilarasan M 2021 Physiological and Molecular Plant Pathology Molecular and metabolomic interventions for identifying potential bioactive molecules to mitigate diseases and their impacts on crop plants Physiol. Mol. Plant Pathol. 114 101624
[49] Mouden S, Klinkhamer P G L, Hae Y and Leiss K A 2017 Towards eco-friendly crop protection: natural deep eutectic solvents and defensive secondary metabolites Phytochem. Rev. 16(5) 935–951
[50] Murphy K M and Zerbe P 2019 Phytochemistry Specialized diterpenoid metabolism in monocot crops: Biosynthesis and chemical diversity Phytochemistry 172 112289
[51] Hassini I, Rios J J, Garcia-ibañez P, Baenas N, Carvajal M and Moreno D A 2019 Comparative effect of elicitors on the physiology and secondary metabolites in broccoli plants J. Plant Physiol. 239 1–9
[52] Yactayo-chang J P, Tang H V, Mendoza J, Christensen S A and Block A K 2020 Plant Defense Chemicals against Insect Pests Agronomy 1156 10
[53] Pivovarov A S, Calahorro F and Walker R J 2019 Na+ / K+ - pump and neurotransmitter membrane receptors Invertebr. Neurosci. 19(1) 1–16
[54] Khare S, Ajey N B S, Imtiyaz S, Km H, Vijaya N and Y. Chanda 2020 Plant secondary metabolites synthesis and their regulations under biotic and abiotic constraints J. Plant Biol. 0123456789
[55] Ebenezer K S, Manivannan R and Punniyamoorthy A 2019 Plant Secondary Metabolites of Antiviral Properties a Rich Medicinal Source for Drug Discovery: A Mini Review 9(5) 161–167
[56] Wink M 2018 Plant Secondary Metabolites Modulate Insect Behavior-Steps Toward Addiction Front. Physiol. 9 1–9
[57] Chatterjee S, Ghosh R and Chandra N. 2019 Inhibition of bio film- and hyphal- development , two virulent features of Candida albicans by secondary metabolites of an endophytic fungus Alternaria tenuissima having broad spectrum antifungal potential Microbiol. Res. 232 126386
[58] Asad R, Khan A, Najeeb S, Hussain S, Xie B and Li Y 2020 Bioactive Secondary Metabolites from Trichoderma spp. against Phytopathogenic Fungi 817(8) 1–22
[59] Zaynab M et al. 2018 Microbial Pathogenesis Role of secondary metabolites in plant defense against pathogens Microb. Pathogens. 124 198–202
[60] Utami U, Nisa C, Putri A Y and Rahmawati E 2019 The potency of secondary metabolites endophytic fungi Trichoderma sp as biocontrol of Colletotrichum sp and Fusarium oxysporum causing disease in chili AIP Conf. Proc. 2120 080020
[61] Sahebi M et al 2017 Profiling secondary metabolites of plant defence mechanisms and oil palm in response to Ganoderma boninense attack Int. Biodeterior. Biodegradation 122 151–164
[62] Smilanich A M et al 2017 Host plant associated enhancement of immunity and survival in virus infected caterpillars J. Invertebr. Pathol. 151 102-112
[63] Yuan W et al. 2019 Maize phenylalanine ammonia-lyases contribute to resistance to Sugarcane mosaic virus infection , most likely through positive regulation of salicylic acid accumulation Molucular Plant Pathol. 20(10) 1365–1378
[64] Luo J et al. 2019 Integrated Transcriptome Analysis Reveals Plant Hormones Jasmonic Acid and Salicylic Acid Coordinate Growth and Defense Responses upon Fungal Infection in Poplar Biomolecules 9(1) 12
[65] Complant S, Brader G, Muzammil S, Sessitsch A, Lebrihi A and Mathieu F 2012 Use of beneficial bacteria and their secondary metabolites to control grapevine pathogen diseases BioControl 58(4) 435-455
[66] Actino I, Abo-zaid G A, Matar S M and Abdelkhalek A 2020 Induction of Plant Resistance against Tobacco Mosaic Virus Using the Biocontrol Agent Agronomy 1620(10) 1–16
[67] Peritore-galve F C, Tancos M A and Smart C D 2021 Taxonomy of the Clavibacter Genus Epidemiology in the Field and in Greenhouse Production,” Plant Dis. October 1–15
[68] Bouwmeester H, Schuurink R, Bleeker P and Schiesti F 2019 The role of volatiles in plant communication Plant J. 1–16
[69] Thakur M, Bhattacharya S, Khosla P K and Puri S 2018 Improving production of plant secondary metabolites through biotic and abiotic elicitation J. Appl. Res. Med. Aromat. Plants, 12 1–12
[70] Jamiołkowska A 2020 Natural Compounds as Elicitors of Plant Resistance Against Diseases and New Biocontrol Strategies Agronomy 10(2) 173
[71] Farag M A, Al-mah D A, Meyer A, Westphal H and Ludger A 2017 Metabolomics reveals biotic and abiotic elicitor effects on the soft coral Sarcophyton ehrenbergi terpenoid content Sci. Rep. 648(7) 1–11
[72] Meraj T et al 2020 Transcriptional Factors Regulate Plant Stress Responses Through Mediating Secondary Metabolism Genes (Basel). 346(11) 1–18
[73] Patel H and Krishnamurthy R 2013 Journal of Pharmacognosy and Phytochemistry Elicitors in Plant Tissue Culture J. Pharmacogn. Phytochem. 2(2) 60–65
[74] Singh A and Dwivedi P 2018 Methyl-jasmonate and salicylic acid as potent elicitors for secondary metabolite production in medicinal plants : A review J. Pharmacogn. Phytochem. 7(1) 750–757
[75] Srivastava M N S 2017 Elicitation : a stimulation of stress in in vitro plant cell / tissue cultures for enhancement of secondary metabolite production Phytochem. Rev. 16(6) 1227–1252