Chapter

Plant Metabolites in Plant Defense Against Pathogens

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Abstract

Medicinal plants are widely used worldwide to treat various diseases. Its widespread use is due in part to the cultural acceptance of traditional medicine in different regions of the world, as well as its effectiveness in treating various diseases. Many of its active substances or secondary metabolites are formed to a response of various situations that generate stress in their habitat, such as sudden changes in environmental temperature, humidity, rain, drought, and infections by phytopathogens (fungi, bacteria, viruses, nematodes, protozoa). The production of these secondary metabolites is a mechanism of defense of plants. In this context, the objective of this chapter is to study the secondary metabolites of medicinal plants that could have a promising application in the control of different phytopathogens in crops of agricultural and economic interest.

Keywords: medicinal plants, phytopathogens, secondary metabolites, pesticides, biotic and abiotic elicitors

1. Introduction

Phytopathogens generally attack plants during their growth, causing alterations in their cellular metabolism and/or interfering with the absorption of nutrients [1]. The crops of cereals, vegetables, and fruits are affected by these organisms during harvest and postharvest [2]. However, one of the main control measures to eradicate phytopathogens is the use of pesticides. Although they are effective, easy to access, and easy to use, they have several disadvantages, generate resistance, and are considered toxic substances, not only for bacteria, fungi, viruses, protozoa, and nematodes but also for the humans, animals, and the environment [3, 4]. In this context, the pesticides can induce acute and chronic toxicity, to persist in the environment and pollute soil and water. So, they are easily incorporated into the food chain, bioaccumulation, and biomagnification [5]. Regarding their toxicity mechanisms, it has been described that they can act as endocrine disruptors and as reactive species that generate oxidative stress in the cell [6–9].

On the other hand, the study of medicinal plants as possible natural sources of obtaining active compound (secondary metabolites) against phytopathogens has gained increasing interest in recent years, due to several aspects, mainly that they are obtained from a natural source through the production or synthesis of secondary metabolites considered as nontoxic such as phenols, flavonoids, terpenes, alkaloids, etc. [10–13]. Another advantage is that phytopathogens still do not develop resistance to the antifungal, antimicrobial, and nematicide effect of the phytochemical

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compounds produced by some medicinal plants. When carrying out an exhaustive search in the literature, it was found that the potential use of the secondary metabolites obtained from medicinal plant extracts is fungicide [14–16]. Most of the research in this area focuses on evaluating the effects of these active compounds on fungi such as *Fusarium*, maybe because it is one of the main phytopathogens that cause economic losses mainly in cereal crops and health problems by their aflatoxins [17, 18]. This chapter shows an overview of the recent research on this topic, emphasizing the effect of biotic and abiotic elicitors on the secondary metabolite production, as well as a brief description of the scientific name of the plant, metabolites with antifungal and antibacterial effect, and their limitations and perspectives of its use in the biological control of phytopathogens.

2. Pesticides in the control of phytopathogens

In the market, there are a variety of pesticides that are used alone or in combination to eradicate, control, or prevent pests [4]. Pesticides can be classified according to the chemical group to which they belong, to their selectivity toward a certain phytopathogen, its mechanism of action, and its use or application. However, the most widely used for their effectiveness and a broad spectrum of activity against various pests and diseases in plants are insecticides, herbicides, and fungicides [4, 19].

Pesticides used in agriculture mainly contaminate the soil by direct application and water by leaching, and it is very easy for them to be present either in trace quantities or high in food and to enter the food chain, which facilitates its accumulation and biomagnification [5, 20]. In general pesticides are considered dangerous substances for living beings since they can produce acute or chronic toxicity; however the magnitude of the poisoning depends on several aspects to be considered such as the physicochemical characteristics of the pesticide, the concentration, the exposure time, the route of entry to organisms, their toxicodynamics and toxicokinetics (absorption, distribution, half-life, metabolism, and elimination), as well as the use of mixtures of different pesticides, the components of their formulation, and the general state of health of the individual [21, 22]. All these aspects influence that pesticides represent a risk or danger for those who use them in the fields of cultivation, as well as for those who consume foods that contain substances in trace quantities in prolonged consumption.

Regarding its toxicity, it has been described that pesticides act as endocrine disruptors and generators of free radicals and enzymatic inhibitors [8, 9]. Unfortunately, the cellular targets to which most of these pesticides are directed coincide with cellular targets that are also present in man, such as the case of the mechanisms of action of organophosphorus insecticides, which inhibit the activity of acetylcholinesterase enzyme present in different insects; unfortunately man and other mammals also have acetylcholinesterase, so their toxicity is not selective toward the pests that they wish to control, but they also affect man, and depending on the magnitude of the poisoning, they can cause death [19–22]. However, until today an ideal pesticide does not exist, and the correct use of herbicides, fungicides, insecticides, etc. has many benefits to control plagues and increase the yield of the crops [19].

3. Secondary metabolites of medicinal plants as biological control of phytopathogens

There are several methods of biological control against phytopathogens. The use of extracts of medicinal plants to eradicate diseases in crops caused mainly by

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viruses, bacteria, and fungi is one of them [23]. The above makes sense if we analyze the fact that plants have mechanisms to protect themselves from both biotic and abiotic stress agents. That is, if the phytopathogens (biotic agents) are attacking the plants, why not think what the plant does to defend itself?

In this context, it is interesting to analyze the secondary metabolism of plants know which phytochemical substances are produced and what biological activity they present.

3.1 The bioactive potential of secondary metabolites derived from the medicinal plant

Plants are formed by a primary metabolism that is responsible for the physiological processes and development of the plant, such as lipids, carbohydrates, and proteins [23]. The secondary metabolism is not essential in the basic processes of plants. However, these bioactive compounds play an important role in the defense of plants, and these secondary metabolites can be classified as phenolic compounds, carotenoids, terpenes, alkaloids, and sulfur compounds, among others, as shown in **Table 1** [24].

Phenolic compounds are aromatic substances formed during the passage of the shikimic acid pathway or mainly the mevalonic pathway. These can be divided into insoluble compounds such as condensed tannins, lignins, and hydroxamic acids bound to the cell walls, and soluble compounds are phenolic acids, flavonoids, and kinases [25]. Carotenoids are lipophilic molecules and are found in plants giving orange tones. The importance of these compounds is the intervention they have in photosynthesis, and they also protect the photosynthetic apparatus from excess

Classification	Types	Example
Terpenes	Monoterpene	Geraniol
	Sesquiterpenes	Humulene
	Diterpenes	Cafestol
	Sesterpenes	Geranylfarsol
	Triterpenes	Squalene
	Sesquarterpenes	Ferrugicadiol
	Tetraterpenes	Lycopenes
	Polyterpenes	Gutta-percha
Phenolics	Coumarin	Hydroxycoumarins
	Furano-coumarins	Psoralin
	Lignin	Resveratrol
	Flavonoids	Quercitin
	Isoflavonoids	Genistein
	Tanins	Tanins acid
N Containing Compounds	Alkaloids	Cocaine
	Cyanogenic glucosides	Dhurrin
	Non-Protein amino acids	Canavanin
S Containing compounds	Glutathione	
	Glucosinolate	β-D-Glucopyrinose
	Thionins	
	Defensins	
	Allinin	

Table 1.
Types of plant secondary metabolites.

energy [25]. The carotenoid contents in plants are affected by various factors, such as plant development, stress conditions, postharvest conditions, or cooking treatments, but the interest of these compounds has been increasing due to their potential antioxidant activity [26]. Terpenes are lipid-soluble compounds that include one- or more five-carbon isoprene units, which are synthesized by all organisms through two pathways, mevalonate and deoxy-D-xylulose [27]. Terpenoids are classified according to the number of isoprene units they contain; terpenes and terpenoids are basic constituents of many types of plant essential oils [28]. Alkaloids are bioactive compounds that generally contain nitrogen derived from an amino acid of great importance because it has physiological and medicinal properties, for example, caffeine, nicotine, morphine, atropine, and quinine [29].

Now well, all these compounds mentioned above help the plants to develop complex defense systems against different types of stress for the survival or the systematic forces in their metabolism for resistance against pests and diseases. Stress provoked in the plant involves several signaling response pathways for pathogens and insects, and some of these response pathways are induced by the microorganisms themselves. Also, the plants have specific recognition and signaling systems allowing them to detect the pathogens and initiate an effective defense response [30, 31]. The defence system broadest have the plants against pathogens are the phenolic compounds (phenylpropanoids and flavonoids). These substances have different mechanisms of action they can dissociate the ions of the phenolic hydroxyl and forming phenolates, ionic and hydrogen bonds with peptides and proteins causing a high astringency and protein denaturation. In the other hand, they interfere with the pathogen's cell signalling compounds and affect their physiological activities through enzymatic inhibition, DNA alkylation and altering their reproductive system [31]. The compounds with allelopathic effects affect positively or negatively on the ecosystem’s structure to remove or eliminate microorganisms from the plants. Some phenolic compounds are allelochemicals that have been shown to have an activity as antibiotics, antifungals, and antipredator [31]. Phenolic acids, such as benzoic, hydroxybenzoic, vanillic, and caffeic, have antimicrobial and antifungal properties produced by the inhibition of enzymes. Caffeic, chlorogenic, sinapic, ferulic, and p-coumaric acids have antioxidant activity by the inhibition of oxidation of lipids and the elimination of reactive oxygen species. These effects are important to the plant defense [32].

3.2 Improving production of plant secondary metabolites through biotic and abiotic stresses

Classification of secondary metabolites related to the defense of plants is commonly used in the form of synthesis and accumulation of phytochemicals with interaction effect of the pathogenic plant against plant insect, virus, fungi, and antibacterial compounds. For example, phytoalexins are produced very quickly after infection of a pathogen producing toxicity to an ambiguous environment of fungi or bacteria [33, 34].

Phenylpropanoids and flavonoids have hydroxyl groups that contain phenolic compounds, which dissociate into phenolate ions, and the phenolic hydroxyl groups form ionic bonds and hydrogen bonds with peptides and protons, producing a high astringency and denaturation that thus show an antifungal effect acting together with cellular signaling compounds and physiological activities or acting on the parts of the pathogen, reproductive system, enzymatic inhibition, etc. [35]. The properties of the proteins change with any change in protein conformation, for example, by changing the three-dimensional structure forming covalent bonds with SH, OH or free amino groups there is inactivation or protein function loss. When polyphenols of the plants bind to some proteins of phytopathogens are less toxic for them but can protect the plant of abiotic elicitors [36]. On the other hand, phytoalexins are induced against the attack of microbes and insects activated by β-glucosidase by the release of biocidal aglycones [37]. In the same way act the benzoxazinoids (BX), these phytochemical compounds are produced and released by tissue damage and hydrolysis by β-glucosidase and act as insect repellents too [38].

At present, several biotechnological strategies have been used to increase the productivity of secondary metabolites, using different inducers of secondary metabolites such as at the cellular, organic, and plant levels, as well as the most effective methods to improve the synthesis of these secondary metabolites in endemic and medicinal plants [39]. These secondary metabolites accumulate in plants when they are prone to various stress types, inducers, or signal molecules. Thus, there are different modulating factors of secondary metabolites, as well as microbial, physical, or chemical effects such as abiotic or biotic elicitors, inducing the biosynthesis of specific compound that plays an important role in the adaptations of plants to stress conditions, and these phenomena cause a greater synthesis and accumulation of secondary metabolites [40]. In **Table 2** the authors focus on the abiotic elicitors that are substances of biological origin such as proteins and carbohydrates that are initiator compounds or coupling responses at the cellular level activating several enzymes or signaling canals. There are also microorganisms and chemical compounds with elicitor effect that stress the plant and produce the expression of a greater amount of metabolites or new metabolites which cause physiological changes in the plant against pathogens. As shown in **Table 2**, glycoprotein-type proteins produce phytoalexins that have been used to identify ion channels in cell membranes and thus transfer signals by external stimuli, as demonstrated by Alami [41] where the *Plantanus x acerifolia* cultures were applied to an inducer of *Ceratocystis fimbriata* f. sp. These, in turn, induced the synthesis of phytoalexins (hydroxycoumarin, scopoletin, and umbelliferone), and upon isolating the glycoprotein produced the synthesis of coumarin by 80%. On the other hand, oligogalacturonic acids are found in the cell wall of the plant inducing the biosynthesis of phytoalexins, whereas chitin is found in the cell wall of fungi, generating signaling factors in plants such as *Hypericum perforatum* production stress in the plant and increasing the production of phenolic compounds for their defense against pathogens [39, 42]. Rhizobacteria function as modelers of secondary metabolites with pharmacological activity. Rhizobacteria colonize the rhizospheres of the plants and improve the growth of the plant, being localized in the bark or root nodules acting as inducers of the enzymes that participate in the metabolic pathways of bioactive compounds and jasmonic acid biosynthesis; these act as signal transducers [43, 44]. Other signal inducers are the mycorrhizal fungi that help the plant to absorb more water and show defense against other pathogens such as fungi, bacteria, or parasites that affect the roots of the plant. These mycorrhizal fungi produce secondary metabolites such as phenolic compounds and alkaloids, among others [45–48]. Elicitors such as salicylic acid, jasmonic acid, hydrogen peroxide, chitosan, etc. act as plant hormones in the expression of genes interacting as target signaling causing a physiological response in the plant which increases the production of phenolic compounds, vitamin C, carotenoids, or defense stimuli against pathogens; there are also synergistic effects between salicylic acid and jasmonic acid providing resistance against pathogens by the induction of the octadecanoic acid pathway [49–52, 53].

On the other hand, **Table 3** shows some research that has the influence of different abiotic elicitors that are considered substance and that are not of biological origin such as salt, drought, light or heavy metals, and temperature, among others. **Table 3** shows different perspectives of research on medicinal or aromatic plants in hydroponic crops, outdoors, and the application of elicitors in different stages of growth or postharvest. For example, heavy metals such as Al^{3+}, Cr^{3+}, Co^{2+}, Ni^{2+},

Classification	Elicitor/ Species	Compounds	Plant Species	References
Proteins	Glycoprotein	Coumarin	*Plantanus acerifolia*	[41]
Carbohydrates	Chitosan	Phytoalexin	*Nicotiana tabacum* *Eschscholzia californica*	[54]
	Ologogalacturonic acid	Saponin	*Panax ginseng*	[55]
	Ologogalacturonic acid	Trans-resveratrol Viniferins	*Vitis vinifera*	[56]
	Chitin Pectin	Hipericin Pseudohypericin	*Hipericum perforatum*	[39]
	Chitin	Phenilpropanoid Naphtodianthrone	*Hipericum perforatum*	[42]
	Chitosan	Curcumin	*Curcuma longa* L.	[40]
	Chitosan	Withaferin	*Wiyhania somnifera*	[57]
Plant growth promoting rhizobacteria (PGPR)	*Pseudomonas putida* *Pseudomonas fluorescens*	Cis-Thujone Camphor 1,8-cineole	*Salvia officinalis*	[58]
	Pseudomonas fluorescens *Bacillus subtilis* *Azospirillum brasilense* *Bacillus solanum*	γ- terpinene Trans-sabinene hydrate Cis- sabinene hydrate Thymol	*Origanum majoricum*	[59]
	Glomus aggregatum *Bacillus coagulans* *Trichoderma harzianum*	Phenols Tannins Flavonoids Saponins Alkaloids	*Solanum viarum*	[43]
	Bacillus polymyxa *Pseudomonas putida* *Azotobacter chroococcum* *Glomus intraradices*	Stevioside	*Stevia rebaudiana*	[42]
	Bacillus subtilis	Phenolic compounds (gallic, cinnamic, ferulic acid)	*Ocimum basilicum*	[60]
	Pseudomonas flurescens *Azopirillum brasilense*	Monoterpenes Phenolic compounds	*Tagetes minuta*	[61]
Fungus	*Fusarium oxysporum* *Botrytis cinerea*	Phenylpropanoid Naphtodianthrone	*Hypericum perforatum*	[42]
	Phytopthora megaspema *Rhizopus arrhizus*	Alkaloids (tropane)	*Datura stramonium*	[45]
	Aspergillus niger	Rosmarinic acid	*Ocimum basilium*	[46]
	Rhizostonia solani	Sesquiterpenes	*Hyoscyamus muticus*	[47]
Phytohormones	Abscisic acid Gibberellin	Phenolic acids Tanshinones	*Salvia miltiorrhiza*	[48, 62]
	Ethylene	Anthocyanin	*Fragaria ananassa*	[63]
	Gibberellic acid	Caffeic acid derivatives	*Echinacea pupurea*	[64]
Elicitors	Salicylic acid	Stilbene Tanshinones Monoterpene Gymnemic acid	*Vitis vinifera* *Salvia miltiorrhiza* *Houttuynia cordata* *Gymnema sylvestre*	[49-52]
	Methyl salicilate	Withaferin A	*Withania somnifera*	[57]
	Methyl Jasmonate	Anthocynin Stilbene Trans-resveratrol Rosmarinic acid Saponin Soyasaponin	*Vitis vinifera* *Mentha piperita* *Glycyrrhiza globa*	[56, 53, 54]
	Jasmonic acid	Plumgagin	*Plumbago indica* *Plumbago rosea*	[53]

Table 2.
Effect of biotic elicitor on the production of various secondary metabolites in plants [54–64].

Classification	Elicitor/ Species	Compounds	Plant Species	References
Heavy metals	Al^{3+}, Cr^{3+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Cd^{2+}	Sesquiterpenoid Lubimin 3-hydroxylubimin	*Datura stramonium*	[70, 71]
	Ag^{+}	Atropine	*Salvia castanea* *Datura metel*	[72]
	Cd^{2+}, Co^{2+}, Ag^{+}	Resveratrol	*Vitis vinifera*	[73]
	Ca^{2+}, Mg^{2+}, Mn^{2+}, n^{2+}, Cu^{2+}, Fe^{2+}, Co^{2+}	Betalain	*Beta vulgaris*	[74]
Temperature	High temperature	Hypericin Hyperforin Ginsenoside	*Hypericum perforatum* *Panax quinqufolius*	[65, 75]
	Low temperature	Melatonin Anthocyanin	*Rhodiola cremulata* *Melastoma malabathricum*	[66, 78]
Light	UV-B light	Vinblastine Vincristine	*Catharanthus roseus*	[66]
	UV-C irradiation	Flavonoid Stilbene	*Catharanthus roseus*	[78]
	Light radiation	Anthocyanins	*Melastoma malabathric*	[77]
Salinity	Salinity	Sorbitol Jasmonic acid Flavonoids Anthocyanin GABA Phenylpropeno	*Lycopersicum esculentum* *Hordeum vulgare* *Brivillea ilicifolia* *G. Arenaria* *Sesamum indicum*	[67-79]
Drought	Drought stress	Rosmarinic Ursolic Oleanolic acid	*Prunella vulagaris*	[80]
	Water Stress	Salvianolic acid	*Salvia miltiorrhiza*	[68]
	Drought	Steviol glycosides	*Stevia rebaudiana*	[69]
	Water Osmotic imbalance	Hypericin	*Hypericum perforatum*	[81]

Table 3.
Effect of abiotic elicitor on the production of various secondary metabolites in plants [70–81].

Cu^{2+}, Zn^{2+}, and Cd^{2+}, among others, are considered high toxicity compounds depending on the concentrations applied in the sprinkler system or because they are used as biocontrol since they alter the production of metabolites in plants. Similarly, Zobayed [65] demonstrated that the temperature in high concentrations in *Panax quinqufolius* improves the senescence of the leaves and produces a greater quantity of bioactive compounds in the root of the plant. So the investigations using high or low temperatures demonstrate the production of secondary metabolites, but the temperatures that have been investigated the most are the low producing physiological changes in the plant, increasing the lignification by the production of suberin in the cell wall and the metabolites such as sorbitol, raffinose, proline, melatonin, anthocyanins, etc. However, light by means of ultraviolet radiations generates the production of essential oils and phenolic compounds and decreases the production of toxic compounds in some plants [66]. On the other hand, salinity and drought produce death leading to cellular dehydration or osmotic stress and in certain concentrations can reduce the growth or development of plants but alter many physiological and metabolic processes that stimulate the production of polyphenolic compounds, anthocyanins, terpenes, and alkaloids, among others. Salinity can be produced in plants by ionic or osmotic means and drought by environmental or intentional changes due to water deficit which are always accompanied by temperature or solar radiation [67–69]. Then we can say that the biotic and abiotic factors are modular secondary metabolites influencing the metabolic level and the production of secondary metabolites. Therefore, the current research focuses on the use of elicitors, for the regulation of metabolic pathways, and target signaling in genes that influence the overproduction of secondary metabolites using various applications but taking care of the production performance of fruits, vegetables, or different plants.

Recent studies focused on evaluating the secondary metabolites of medicinal plants that are active against phytopathogens show that the potential use that these compounds can have in the future is for the control of phytopathogenic fungi, mainly against different species of *Fusarium* [14–16]. In this regard, the most active compounds have been found mainly in the essential oil obtained from the aerial parts of various medicinal plants, which suggests that the bioactive compounds are liposoluble; this may explain why they are active mainly against fungi, because the cell wall of these specimens are composed mainly of ergosterol, the active liposoluble compounds present in the essential oil to easily cross the cell wall of the fungus and in the interior act on their cell target, or they can alter the permeability of the wall of the fungus [82]. It can cause rupture and lysis of the fungal cell; however, it is necessary to study the toxicodynamics of these substances in order for them to know how to act in the fungi cell. On the other hand, the antifungal activity has been evaluated in *vitro*, by the agar diffusion and microdilution method; in general terms the range of the evaluated IC50 varies in a range that goes from 0.0035 to 8 mg/ml of the extract. It is important to mention that one of the main limitations of these studies is that this activity has only been evaluated at the laboratory level [83–85]. **Table 4** shows different types of extracts made with medicinal plants, and their biological activity reported *in vitro* tests at the laboratory level.

Finally, in the realization of a retrospective of the secondary metabolite modulating factors in our workgroup, Garcia-Mier [95] demonstrated that the use of mixtures of elicitors such as jasmonic acid, hydrogen peroxide, and chitosan in different concentrations applied in various stages of plant development of the sweet bell red pepper and in different stages of ripening of the fruit has a positive effect on the increase of polyphenolic and carotenoid compounds, where the results showed that the maturation stage of 95% produces a greater quantity of bioactive compounds. On the other hand, Vargas-Hernández [96] demonstrated that the foliar application of hydrogen peroxide in *Capsicum chinense* Jacq. has an effect on the antimicrobial activity, where the different concentrations of hydrogen peroxide potentiated the production of secondary metabolites such as flavonoids, capsaicin, and dihydrocapsaicin, where these metabolites had an effect on microorganisms such as *Staphylococcus aureus*, *Escherichia coli*, *Streptococcus mutant*, *Salmonella thompson*, *Listeria monocytogenes*, *Streptococcus faecalis*, and *Candida albicans*, and the results showed that the application of hydrogen peroxide increases the inhibitory effect against pathogenic microorganisms, showing greater activity against *S. aureus*, *S. Thompson*, and *C. albicans* in the jaguar variety, while the variety Chichen-Itza was more potent against *E. faecalis* and *E. coli*. Also, Zunun-Pérez [97] evaluated the effect of modulating factors of secondary metabolites by spray application that is performed in *Capsicum annuum* L. in weekly applications and 1 day before collection with elicitors such as hydrogen peroxide, salicylic acid, and oligosaccharide of xyloglucan on capsiate concentration and the expression of genes such as phenylalanine ammonia-lyase, aminotransferase, capsaicin synthase, and β-keto acyl synthase where the results showed that hydrogen peroxide in weekly applications significantly increases capsiate concentrations and gene expression and the yields of the production of the plant are not affected by the application of these elicitors.

Medicinal Plant	Type of Extract	Phytochemistry Compounds	Biological Activity Aginst	Reference
Acacia farnesiana	Hydroalcoholic extract	Tannins Flavonoids Saponins Alkaloids Triterpenes Quinones	*Pyricularia grisea* *Phythophthora parasitica* var. *nicotianae*	[86]
Artemisia herba alba	Aqueous extract	Tannins Flavonoids Saponins Steroids Alkaloids	*Fusarium graminearum* *Fusarium sporotrichioides*	[87]
Asphodelus tenuifolius	Aqueous extract	Tannins Flavonoids Steroids Alkaloids	*Fusarium graminearum* *Fusarium sporotrichioides*	[87]
Bauhinia galpinii	Methanol:Dichloromethane extract	Phenols Flavonoids	*Aspergillus parasiticus* *Aspergillius flavus*	[88]
Breonadia salicina	Hexane and Methanol extracts	No data	*Penicillium janthinellum* *Trichoderma harzianum* *Fusarium oxysporum*	[89]
Bucida buceras	Hexane, Dichloromethane, Acetone and Methanol extracts	No data	*Penicillium janthinellum* *Penicillium expansum* *Trichoderma harzianum* *Fusarium oxysporum*	[89]
Carpobrotus eludis	Methanol:Dichloromethane extract	Phenols Flavonoids	*Aspergillus parasiticus*	[88]
Cotula cinerea	Aqueous extract	Tannins Flavonoids Saponins Alkaloids	*Fusarium graminearum* *Fusarium sporotrichioides*	[87]
Euphorbia guyoniana	Aqueous extract	Tannins Flavonoids Saponins Steroids Alkaloids Anthocyanins	*Fusarium graminearum* *Fusarium sporotrichioides*	[87]
Harpephyllum caffrum	Acetone and Methanol extracts Methanol:Dichloromethane extract	No data Phenols Flavonoids	*Penicillium janthinellu,* *Trichoderma harzianum* *Fusarium oxysporum* *Aspergillus parasiticus* *Aspergillus ochraceous*	[88, 89]
Maesa lanceolata	Methanol:Dichloromethane extract	Phenols Flavonoids	*Aspergillus parasiticus*	[88]
Milletia grandis (E. Mey)	Aqueous, Methanol:Dichloro methane extracts	Phenols Flavonoids	*Aspergillus ochraceous* *Fusarium graminearum* *Furasium oxysporum*	[88]
Morinda citrifolia L.	Essential oil	Methyl octanoate, Octanoic acid, Ethyl octanoate, Isopentyl hexanoate, 3- Methyl-2-butenyl hexanoate, 3-Methylbutyl octanoate, Methylbutyl-2-enyl octanoate	*Exserohilum turcicum*	[90]
Olinia ventosa	Hexane, Dichloromethane, Acetone and Methanol extracts	No data	*Trichoderma harzianum*	[89]
Parthenium hysterophorus	Hydroalcoholic extract	Tannins Flavonoids Saponins Amino acids Triterpenes Phenols	*Pyricularia grisea* *Phytophthora parasitica* var. *nicotianae.* *Phythophthora parasitica* *Fusarium oxysporium* *Stemphylium solani* Weber	[86]
Pluchea carlinensi	Hydroalcoholic extract	Phenols Tannins Flavonoids Saponins Steroids Alkaloids Quinone	*Pyricularia grisea* *Phytophthora parasitica* var. *nicotianae.* *Phythophthora parasitica* *Fusarium oxysporium* *Stemphylium solani* Weber	[86]

Ricinus communis	Methanol:Dichloromethane extract	Phenols Flavonoids	*Aspergillus parasiticus Fusarium verticillioides*	[88]
Salvia africana- lutea L.	Methanol:Dichloromethane extract	Propanoic acid, Dodecane Phosphoric acid, Glycerol, Succinic acid, Malic acid Pentadecane, Rythronic acid, Xylitol, Ribitol, 2-keto-1-gluconic acid, 1,3-dibromobicyclon, D-fructose, Fructose oxime, D-glucose, D-	*Fusarium verticillioides Fusarium proliferatum*	[91]
		mannose, D-galactose, Sedoheptulose, o-methyloxime, Galactonic acid, Hexadecanoic acid Myo-inositol, Mannitol Caffeic acid, Octadecanoic acid, Alpha-D-glucopyranoside, Octacosane		
Solanum panduriforme	Methanol:Dichlomethane extract	Phenols Flavonoids	*Aspergillius parasiticus Aspergillius ochraceous Fusarium graminearum Fusarium oxysporum*	[88]
Solidago canadensis L.	Essential oil	Germacrene D, limonene, α-pinene, β-elemene, and bornyl acetate. Camphene, α-caryophyllene, sesquisabinene bicyclosesquiphellandrene, β-cadinene, β-caryophyllene, β-pinene, β-sabinene Hydrocarbon monoterpenes, Oxygenated monoterpenes, Sesquiterpene hydrocarbons	*Monilinia fructicola Botrytis cinerea Aspergillus niger Penicillium expansum Bacillus megaterium Clavibacter michiganensis Xanthomonas campestris Pseudomonas fluorescens Pseudomonas syringae* pv. *phaseolicola*	[92]
Thymus capitatus	Essential oil	Thymol Carvacrol	*Aspergillus niger Aspergillus oryzae Penicillium digitatum Fusarium solani*	[93]
Vangueria infausta	Dichloromethane and Acetone extracts	No data	*Aspergillius parasiticus Trichoderma harzianum*	[89]
Viola odorata L.	Methanol:Water extract	Cyclotides: cyO2, cyO3, cyO13, and cyO19	*Fusarium oxysporum Fusarium graminearum Fusarium culmorum Mycosphaerella fragariae Botrytis cinerea Pseudomonas. syringae* pv. *syringae Pectobacterium atrosepticum Dickeya dadantii*	[94]
Waburgia salutaris	Methanol:Dichlomethane extract	Phenols Flavonoids	*Aspergillius parasiticus Aspergillius ochraceous Fusarium verticillioides Fusarium oxysporum*	[88]
Xylotheca kraussiana	Dichloromethane and Acetone extracts	No data	*Trichoderma harzianum Fusarium oxysporum*	[89]
Ziziphus mucronata	Methanol:Dichlomethane extract	Phenols Flavonoids	*Fusarium graminearum*	[88]

Table 4.
Secondary metabolites of medicinal plants with biological activity against phytopathogens [86–94].

4. Conclusions

The phytochemicals that produce medicinal plants derived from their secondary metabolism represent a safe and effective alternative to control various phytopathogens that affect various crops of agricultural products of economic and nutritional interest. There are different challenges in the use of biopesticides obtained from medicinal plants, such as evaluating the costs of obtaining these compounds on a large scale or exploring the possibility of them being obtained through chemical synthesis to increase yield and reduce costs. On the other hand, the various studies that exist on the effectiveness of these compounds are only at the laboratory level, which is why it is still necessary to explore and evaluate their effectiveness at the greenhouse and field levels.

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Conflict of interest

The authors declare no conflict of interest.

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