Din A *et al.* (2023)
Notulae Botanicae Horti Agrobotanici Cluj-Napoca
Volume 51, Issue 1, Article number 12991
DOI:10.15835/nbha51112991
Review Article

Natural compounds: an effective and eco-friendly strategies for controlling and combating plant pathogens

Alin DIN[1,2]*, Ion MITREA[1], Rodi MITREA[1]

[1]*University of Craiova, Faculty of Horticulture, 13 A.I. Cuza Street, Craiova, Dolj, Romania; din.alin96@yahoo.com (*corresponding author); mitreaion@yahoo.com; rodimitrea@yahoo.com*
[2]*National Research and Development Institute for Biotechnology in Horticulture Stefanesti Arges, Romania*

Abstract

Currently, the management of phytopathogenic agents is an ongoing challenge globally, as they cause major damage in agricultural plantations. However, the use of synthetic pesticides currently in use has negative effects on the environment and on the living organisms that develop their life cycle in these habitats. For this reason, research in the last decade has led to the identification and exploitation of natural compounds with important antifungal properties as natural alternatives to combat and control pathogens. This review is based on the description of plant extracts, essential oils and natural compounds with important anti-fungal properties. However, their direct application to plants is difficult, because their adhesion and persistence in environmental conditions does not allow this fact. The current challenge is to develop formulations based on natural compounds that retain their properties over time in order to be applied to agricultural crops.

Keywords: essential oils; natural compounds; plant protection; phytopathogens; plant extract

Introduction

Phytopathogenic fungi represents infectious agents of plants, producing changes in different stages of plant development, even after harvesting during storage. There are numerous fungal species that cause serious damage to agricultural products, because they affect the quality of fruits and vegetables (nutritional values, organoleptic characteristics, etc.). More than 25% of cereals (wheat, corn, rice, etc.) are contaminated in most cases by fungi belonging to the genera *Fusarium* and *Aspergillus*, which are indirectly responsible for the production of alphatoxin B1, which is toxic and highly carcinogenic, as well as more than 300 fungal metabolites, which can generate metabolic disorders or even poisoning. (Satish *et al*., 2007; Díaz-Dellavalle *et al*., 2011; Lee *et al*., 2007). In the study by Stracquadanio *et al*. (2021), it was shown that natural extracts obtained from *Trichoderma asperellum* and *Trichoderma atroviride* applied to tomatoes, wheat and maize, reduced the production of ochratoxin A. In addition, the extracts reduced the production of mycotoxins in a dose-dependent manner and with a long-lasting effect.

Plants are a rich source of different chemical compounds such as: alkaloids, flavones and flavonoids, phenols, terpenes, tannins or quinones. Produced as secondary metabolites, they can constitute up to 30% of the dry mass of plants, having an essential role in their protection against pathogens, abiotic stress factors, but

Received: 08 Nov 2022. Received in revised form: 20 Mar 2023. Accepted: 22 Mar 2023. Published online: 29 Mar 2023.
From Volume 49, Issue 1, 2021, Notulae Botanicae Horti Agrobotanici Cluj-Napoca journal uses article numbers in place of the traditional method of continuous pagination through the volume. The journal will continue to appear quarterly, as before, with four annual numbers.

also against herbivores. Due to their specific properties, plants have been used since ancient times for medicinal purposes, but also as food additives. Nowadays, the recognition of the chemical structure and functions of certain plant compounds allows us to extract and isolate them for use as ingredients in the cosmetic, food, pharmaceutical, industries etc. There is also great interest in their application as biopesticides, fungicides and insecticides to protect crop plants (Mazid *et al*., 2011; Bhagat *et al*., 2014).

The use of phytopreparations but also of essential oils represents the true means of perspective for the biological protection of plants, having numerous advantages, such as: the use of these preparations has demonstrated an effective impact on phytopathogens, the extraction is not complicated and long-lasting, does not pose a danger to the environment and people, they decompose quickly in agrocenosis, also proving an increased efficiency (Zarins *et al*., 2009). Studying of the effectiveness of plant extracts led to the premise that they can be used as alternative bioformulations to the currently used synthetic fungicides, due to their antifungal activities, the low level of toxicity for humans and the environment, but also biodegradation. (Du Plooy *et al*., 2009; Tripathi and Dubey, 2004).

Plant extracts and essential oils

Algae extracts have been shown to be a possible substitute for synthetic pesticides, as demonstrated by the study of Jiménez *et al*. (2011) who evaluated the antifungal potential of extracts from the brown alga *Lessonia trabeculata* and observed that it reduced tomato leaf lesions following *Botrytis cinerea* infection. They also observed that aqueous and ethanolic extracts of the red alga *Gracillaria chilensis* inhibited the growth of *Phytophthora cinnamomi*. In addition, there are numerous studies that refer to the antifungal activity of brown algae extracts against fungal species, *Cladosporium herbarum*, *Botrytis cinerea*, *Cladosporium herbarum*, *Phialophora cinerescens*, *Phoma tracheiphila*, *Sclerotinia sclerotiorum*, *Sclerotium rolfsii* and *Verticillium dahliae* being just a few species of fungi pathogens that showed sensitivity to algae extracts obtained from species belonging to the *Phaeophyceae* class (Fenical and Sims, 1973; Moreau *et al*., 1988; Belattmania *et al*., 2016; Esserti *et al*., 2017; Mohamed and Saber, 2019; Vicente *et al*., 2021). So, it was found that the potential of the activities presented by the metabolites produced by seaweed is strongly influenced by both the environment and the biological factors (Khaleafa *et al*., 1975; Ballantine *et al*., 1987; Robles-Centeno *et al*., 1996; Kumar *et al*., 2000; Jiménez *et al*., 2011; Vicente *et al*., 2021). Ashwani *et al*. (2011) observed high efficacy of aqueous extracts of *Cannabis sativa*, *Parthenium hysterophorus*, *Urtica dioica*, *Polystichum squarrosum* and *Adiantum venustum* against five phytopathogens of high economic importance namely *Alternaria solani* on tomatoes, *Alternaria zinnia* on *Zinnia* sp., *Curvularia lunata* on corn, *Rhizoctonia solani* on potatoes and *Fusarium oxysporum* on tomatoes. Notable results were also obtained by Al-Rahmah *et al*. (2013) who evaluated the antifungal potential of natural extracts obtained from *Lantana camara*, *Salvadora persica*, *Thymus vulgaris*, *Zingiber officinale* and *Ziziphus spina* on phytopathogens found in tomatoes: *Fusarium oxysporum*, *Pythium aphanidermatum* and *Rhizoctonia solani*. The extracts of *Salvadora persica*, *Thymus vulgaris* and *Zingiber officinale* showed a good fungistatic action on the previously mentioned phytopathogenic fungi.

The antifungal properties of the extracts obtained from *Ricinus communis* and *Chromolaena odorata* were tested by Nahunnaro and Bayaso (2012) against the fungus *Alternaria solani*, the results obtained being encouraging in the biological control of this phytopathogen. Thyme essential oil is also known for its antifungal effects, which is why Wu *et al*. (2011) tested the potential against the phytopathogen *Alternaria alternata*, the inhibition percentage being over 60% at the concentration of 500 μL/L. Askarne *et al*. (2012) evaluated the antifungal activity of 50 plant species collected in different regions of southern Morocco. Thus, it was demonstrated that *Anvillea radiata* and *Thymus leptobotrys* completely inhibited the mycelial growth of the pathogenic fungus *Penicillium italicum* at concentrations of 10%. Promising results were also obtained by Şesan *et al*. (2015) who evaluated the antifungal potential of natural extracts obtained from *Achillea millefolium*, *Allium sativum*, *Artemisia dracunculus* '*Sativa*', *Hyssopus officinalis*, *Mentha* sp., *Rosmarinus officinalis*, *Satureja hortensis*, *Tagetes patula*, *Valeriana officinalis*. The extracts were used in three different concentrations namely 5%, 10% and 20%. The highest efficacy (100%) against the phytopathogen *Botrytis cinerea* was demonstrated by the extract obtained from *Hyssopus officinalis*, at all three concentrations used, followed by the extract from *Satureja hortensis*. The extract obtained from *Allium sativum* and *Mentha* sp. it is observed that they are effective only at high concentration, 10% and 20% respectively. However, the study by Shalini *et al*. (2019) suggest that neem oil and aqueous extracts obtained from *Allium sativum*, *Leucas martinicensis and Zingiber officinale* can be used to control the phytopathogen *Diplocarpon rosae*. However, the neem oil tested on the affected plants showed a phytotoxic effect compared to the other extracts used. The inhibitory effect of *Salvia officinalis* extract was tested against the fungus *Phakopsora pachyrhizi* that produces Asian rust, one of the most important diseases of soybean crops. The fungus is very aggressive causing significant damage to farmers, chemical control is not exactly easy. From the studies carried out, a potential substitute for classic pesticides can be considered the extract from *Salvia officinalis* that was studied by Borges *et al*. (2013), they observed a germination percentage below 15%. In 2010, Schuster *et al*. (2010) used extract obtained from the species *Glycyrrhiza glabra* against six plant pathogens, *Phytophthora infestans*, *Pseudoperonospora cubensis*, *Podosphaera xanthii*, *Blumeria graminis*, *Uromyces appendiculatus* and *Botrytis cinerea*. The previous study shows that three of the six phytopathogens, *Phytophthora infestans*, *Pseudoperonospora cubensis* and *Uromyces appendiculatus*, showed increased sensitivity using the 5% concentration of the extract.

Keeping pace with the activity of antifungal extracts, a number of five extracts obtained from *Artemisia absinthium*, *Rumex obtusifolius*, *Taraxacum officinale*, *Plantago lanceolata* and *Malva sylvestris* were tested as natural alternatives in the control and combat of phytopathogenic fungi *Alternaria alternata*, *Penicillium expansum* and *Mucor piriformis*. The percentage of inhibition for all tested extracts being over 60% on the three tested phytopathogens (Parveen *et al*., 2014). Moreover, *Capsicum* extract shows important antifungal properties against the pathogenic fungus Colletorichum gloeosporioides. (Mihaescu and Neagu Frăsin, 2020).

The efficacy of garlic (*Allium sativum*) extract against the phytopathogen *Fulvia fulva* was reported by Ting-Ting *et al*. (2011) where it was demonstrated that at the concentration of 80 mg/mL^{-1} the percentage of inhibition is 100%. According to the study conducted by Ramaiah and Garampalli (2015), the extracts obtained from the species *Solanum indicum*, *Azadirachta indica* and *Oxalis latifolia* demonstrated increased efficacy against the phytopathogen *Fusarium oxysporum* f. sp. *lycopersici*, their inhibition percentage being over 70% of the colony diameter.

The essential oils of *Rosmarinus officinalis* and *Thymbra spicata* were tested against the phytopathogen *Monilinia fructigena* and the potential for use of both essential oils was shown to be high. However, *Thymbra spicata* essential oil at a concentration of 2 µl and demonstrated 100% efficacy, while *Rosmarinus officinalis* essential oil at a concentration of 16 µl was shown to completely inhibit mycelial development (Yilar and Bayar, 2018).

In addition, *Cymbopogon citratus* oil at a concentration of 500 ppm has been shown to completely inhibit sporulation and germ tube generation of the fungal species *Colletotrichum coccodes*, *Botritys cinerea*, *Rhizopus stolonifer* and *Cladosporium herbarum*. (Trösken *et al*., 2004; Jiménez-Reyes et al., 2019). In contrast, according to the study by Chang *et al*. (2008) the oil of *Calocedrus macrolepisa* var. *formosana* showed an important antifungal activity, up to 65% against *Pestalotiopsis funerea* and 52% against the phytopathogen *Fusarium solani*. Antifungal activity of *Xanthium strumarium* essential oil was demonstrated by Sharifi-Rad *et al*. (2015), where it was found to reduce mycelial growth of the phytopathogenic species *Aspergillus niger* by up to 34%. Another oil with properties to prevent and fight against the pathogen *Botrytis cinerea* is ginger. (Tripathi *et al*., 2008; JIménez-Reyesa *et al*., 2019).

Major groups of natural compounds with antifungal potential

Phenolic compounds

In recent years a number of studies have been reported on the antifungal potential of phenolic compounds obtained from natural sources. The positions and number of hydroxyl groups in the phenolic group are believed to be closely related to their toxicity relationship against microorganisms. Thus, the mechanisms considered to be responsible for the toxicity of phenols against microorganisms include enzymatic inhibition by oxidized compounds, possibly by reaction with sulfhydryl groups or by nonspecific interactions with proteins. Among the polyphenols, flavan-3-ols, flavonols and tannins have received the most attention due to their broad spectrum and greater antimicrobial activity compared to other polyphenols, as well as the fact that most of them are able to suppress a number of microbial virulence factors (such as: inhibition of biofilm formation, reduction of host ligand adhesion and neutralization of bacterial toxins) showing synergy with antibiotics (Daglia, 2012). Antibacterial properties of phenolics may also be due to iron deficiency or hydrogen bonding with vital proteins such as microbial enzymes (Sanhueza *et al*., 2014; Kabir *et al*., 2015).

Flavones are phenolic structures whose chemical structure contains a carbonyl and a 3-hydroxyl group. Thus, the amentoflavones obtained from *Selaginella tamariscina* demonstrated an important antifungal action against the phytopathogen *Aspergillus flavus* (40 µg/100 µl), a fact demonstrated by Jun Jung *et al*. (2006). A series of four compounds, eupomatenoid-3, eupomatenoid-5, conocarpan and orientin, from *Piper solmsianum* showed antifungal activity against all tested dermatophytes (*Aspergillus flavus*, *Aspergillus fumigatus*, *Aspergillus niger*, *Aspergillus niger*, *Microsporum cani*, *Microsporum gypseum*, *Trichophyton mentagrophytes*, *Trichophyton rubrum*, *Epidermophyton flocosum*, *Cryptococcus neoformans*, *Candida albicans*, *Candida tropicalis*) with values in the range of 2.0-60.0 mg/ml (De Campos *et al*., 2005).

The mechanism by which phenolic compounds act focuses on altering the cytoplasmic membrane, causing cell lysis, and can directly inhibit cellular proteins. These mechanisms are what allow the inhibition of microorganisms (Abad *et al*., 2007; Martínez, 2012). For example, a large number of polyphenols extracted from the leaves of *Rhus muelleri* inhibit the growth of the fungus *Fusarium oxysporum* having a diverse phylogenetic complex (Jasso De Rodríguez *et al*., 2015). Mendoza *et al*. (2011) demonstrated that the flavonoid 5,7-dihydroxy-3,8-dimethoxyflavone, extracted from *Pseudognaphalium robustum*, reduced mycelial growth and partial spore germination of the fungus *Botrytis cinerea*.

Stilbenes, especially resveratrol and its derivatives, have become famous for their positive effects on a wide range of medical conditions, as indicated by a large number of published studies. A less investigated area of research is their antimicrobial properties. Thus, the research of Caruso *et al*. (2011) performed on the phytopathogenic fungus *Botrytis cinerea* highlighted both the antifungal effect of resveratrol and its potential to inhibit the development of conidia. The demonstrated optimal concentration, according to Adrian *et al*. (1997) being between 60-140 µg/mL. Also, against dermatophytes such as *Trichophyton mentagrophytes*, *Trichophyton tonsurans*, *Trichophyton rubrum*, *Epidermophyton floccosum* and *Microsporum gypseum*, the inhibitory activity of resveratrol has been shown to be between values of 25-50 µg/mL (Chan, 2002).

Terpenoid compounds

Terpenes are a large class of aromatic chemicals present in a wide variety of plants, foods and essential oils, and their purpose is to protect plants against fungi, bacteria and animal pests. In general, essential oils have a high concentration of terpenes and sesquiterpenes (Abad *et al*., 2007; Martínez, 2012). The antifungal activity of carrot oil was tested against the pathogen *Alternaria alternata*, the inhibition percentage was 65% of the colony diameter. The main esters found in carrot essential oil are sesquiterpenes such as carotol (Abad *et al*., 2007). Canelo (*Drimys winteri*) essential oil contains varying amounts of polygodial and drimenol (Muñoz-

Concha *et al*., 2007). These terpenes have important antifungal properties against the fungus *Gaeumannomyces graminis* (Monsálvez *et al*., 2010).

Thyme is well known for its antifungal effects, thanks to the thymol found in its oil. Shcherbakova L. *et al*. (2021) through their studies showed that thymol has a remarkable antifungal action. Also, Zhang *et al*. (2016) reported the antifungal efficiency of pure monoterpenes such as: β-citronellol, carvacrol, citral, eugenol, geraniol and thymol against wood white rot fungi: *Trametes hirsuta*, *Schizophyllum commune* and *Pycnoporus sanguineus*. Notable results were also obtained by Xie *et al*. (2017) who confirmed antifungal properties of essential oils from *Origanum vulgare*, *Cymbopogon citratus*, *Thymus vulgaris*, *Pelargonium graveolens*, *Cinnamomum zeylanicum* and *Eugenia caryophyllata* against the wood-decomposing fungi *Trametes hirsuta* and *Laetiporus sulphurous* where the following compounds were highlighted: carvacrol, citron, citronellol, cinnamic aldehyde, eugenol and thymol. The studies carried out by Sempere-Ferre *et al*. (2021) on two pathogens *Botryotinia fuckeliana* and *Rhizoctonia solani* highlighted the antifungal effects of some natural compounds (eugenol, carvacrol, thymol and cinnamic aldehyde).

The first report regarding the production of volatile antibiotics was reported by Strobel *et al*. (2007) who succeeded in isolating the compounds: 2-methylbutanoic acid, 3-methylbutanoic acid, 2-methyl-2-butenal, 3-methyl-3-butene-1-OL, guaiol, 1-octene-3-ethyl, formamide , N-(1-methylpropyl), derivatives of azulene and naphthalene, caryophyllene, phenylethyl alcohol and propanoic acid, from *Muscodor albus* species (*Xylariaceae* family), an endophyte of *Guazuma ulmifolia* species (a *Sterculiaceae* plant collected from the tropical forest-western Ecuador). These compounds were tested against some pathogens of high economic importance, namely: *Botrytis cinerea*, *Mycosphaerella fijiensis*, *Pythium ultimum*, *Phytophthora cinnamomi*, demonstrating their effectiveness by inhibiting the development of the mycelium of the fungi. Also, subsequent reports showed that *Muscodor albus* was also found on other host plant types such as *Myristica fragrans*, *Terminalia prostrata*, *Cinnamomum zeylanicum* and *Ginkgo biloba* (Worapong *et al*., 2001; Ezra and Strobel, 2003; Atmosukarto *et al*., 2005; Lacey and Naven, 2006; Strobel *et al*., 2007; Banerjee *et al*., 2010; Alpha *et al*., 2015). Diterpenoids, sclareol and 13-epi-sclareol isolated from the resinous extract of *Pseudognaphalium cheiranthifolium*, can inhibit the mycelial growth of the phytopathogenic fungus *Botrytis cinerea*, being able to be used as a natural control strategy (Mendoza *et al*., 2015).

Alkaloid compounds

Alkaloids are chemical substances with a wide range of biological activities, usually present in species of the *Solanaceae* family. Thus, hyoscyamine isolated from the medicinal plant *Hyoscyamus muticus* has been shown to inhibit the growth of several species, including *Fusarium dimerum*, *Fusarium nivale* and *Fusarium oxysporum*. (Abdel *et al*., 2009). The study conducted by Soumya and Bindu (2012) highlighted the antifungal potential of capsaicin isolated from the species *Capsicum frutescens*, the tests being performed on four species of fungi, namely *Aspergillus flavus*, *Aspergillus niger*, *Penicillium* sp. and *Rhizopus* sp. Regarding the effectiveness of capsaicin, it was also studied by Buitimea-Cantúa *et al*. (2018) on the phytopathogen *Aspergillus parasiticus*, the inhibitory percentage being set at 50%. The research of Slusarenko *et al*. (2008) demonstrated the effectiveness of allicin obtained from garlic extract against the fungus *Alternaria* sp. Similar results were obtained by Mihaescu *et al*. (2021) who showed that allicin in vitro exhibits a remarkable fungicidal effect against the fungus *Alternaria solani*. Singh *et al*. (2007) demonstrated that alosecurinin or phyllocrysin isolated from the root of *Phyllanthus amarus*, completely inhibits the germination of spores of phytopathogenic fungi *Curvularia* sp., *Curvularia lunata*, *Collectotrichum* sp., *Colletotrichum musae* and *Heterosporium* sp.

Conclusions

The need of the modern era is to obtain pathogen-free and high-productivity crops to meet global food requirements. Because of this, the use of plant extracts has emerged as a natural alternative to synthetic fungicides for controlling and combating phytopathogenic fungi. However, research for the identification and characterization of new compounds with antifungal potential is still a challenge, being the main current approaches in the discovery and development of new biopesticides. Also, following the bibliographic study, we could observe that natural extracts and essential oils from plants present active compounds with important effective antifungal properties. Finally, it could be observed that the phenolic structures represent real starting points for the development of new biopesticides due to the effectiveness they have demonstrated. Another class of compounds that have demonstrated their effectiveness is that of terpenoids, of which the best known are: carvacrol, citral, eugenol, geraniol and thymol, specialized studies confirming their antifungal potential.

Authors' Contributions

Conceptualization: AD and RM; Writing - original draft, review and editing: AD, IM and RM; Supervision and validation: AD, IM and RM.

All authors read and approved the final manuscript

Ethical approval (for researches involving animals or humans)

Not applicable.

Acknowledgements

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

References

Abad MJ, Ansuategui M, Bermejo P (2007). Active antifungal substances from natural sources. Arkivo 7:116-145. *http://dx.doi.org/10.3998/ark.5550190.0008.711*

Abdel F, Nassar M, El-Zayat S, El-Sayed M, Ito S (2009). Responses of fungi to tropane alkaloids produced by a medicinal plant *Hyoscyamus muticus* (Egyptian henbane). Folia Microbiologica 54:207-212. *https://doi.org/10.1007/s12223-009-0033-6*

Adrian M, Jeandet P, Veneau J, Weston LA, Bessis R (1997). Biological activity of resveratrol, a stilbenic compound from grapevines, against *Botrytis cinerea*, the causal agent for gray mold. Journal of Chemical Ecology 23:1689-1702. *https://doi.org/10.1023/B:JOEC.0000006444.79951.75*

Alpha CJ, Campos M, Jacobs-Wagner C, Strobel SA (2015). Mycofumigation by the volatile organic compound-producing fungus *Muscodor albus* induces bacterial cell death through DNA damage. Applied and Environmental Microbiology 81:1147-1156. *https://doi.org/10.1128/AEM.03294-14*

Al-Rahmah AN, Mostafa AA, Abdel-Megeed A, Yakout SM and Hussein SA (2013). Fungicidal activities of certain methanolic plant extracts against tomato phytopathogenic fungi. African Journal of Microbiology Research 7(6):517-524. *http://doi:10.5897/AJMR12.1902*

Ashwani TN, Shipra G, Nandini G and Rajesh K (2011). *In vitro* antifungal potency of plant extracts against five phytopathogens. Brazilian Archives of Biology and Technology 54:1093-1098. *https://doi.org/10.1590/S1516-89132011000600003*

Askarne L, Talibi I, Boubaker H, Boudyach EH, Msanda F, Saadi B, Serghini MA, Aoumar AAB (2012). *In vitro* and *in vivo* antifungal activity of several Moroccan plants against *Penicillium italicum*, the causal agent of citrus blue mold. Crop Protection 40:53-58. *https://doi.org/10.1016/j.cropro.2012.04.023*

Atmosukarto I, Castillo U, Hess WM, Sears J, Strobel G (2005). Isolation and characterization of *Muscodor albus* I-41.3s, a volatile antibiotic producing fungus. Plant Science 169:854-861. *https://doi.org/10.1016/j.plantsci.2005.06.002*

Ballantine DL, Gerwick WH, Velez SM, Alexander E, Guevara P (1987). antibiotic activity of lipid-soluble extracts from Caribbean marine algae. Hydrobiologia 463-469.

Banerjee D, Strobel GA, Booth E, Geary B, Sears J, Spakowicz D, Busse S (2010). An endophytic *Myrothecium inundatum* producing volatile organic compounds. Mycosphere 1(3):229-240.

Belattmania Z, Reani A, Barakate M, Zrid R, Elatouani S, Hassouani M, Eddaoui A, Bentiss F, Sabour B (2016). Antimicrobial, antioxidant and alginate potentials of *Dictyopteris polypodioides* (Dictyotales, Phaeophyceae) from the Moroccan Atlantic Coast. Der Pharma Chemica 8 (2):216-226.

Bhagat S, Birah A, Kumar R, Yadav MS, Chattopadhyay C (2014). Plant disease management: Prospects of pesticides of plant origin. Advances in Plant Biopesticides 119-129. *http://doi.org/10.1007/978-81-322-2006-0_7*

Borges DI, Alves E, Moraes MB, Oliveira DF (2013). Efeito de extratos e óleos essenciais de plantas na germinação de urediniósporos de *Phakopsora pachyrhizi*. Revista Brasileira de Plantas Medicinais 15(3):325-331. *https://doi.org/10.1590/S1516-05722013000300003*

Buitimea-Cantúa GV, Velez-HaroJohn JM, Buitimea-Cantúa NE, Molina-Torres J, Rosas-Burgos EC (2018). GC-EIMS analysis, antifungal and anti-aflatoxigenic activity of *Capsicum chinense* and *Piper nigrum* fruits and their bioactive compounds capsaicin and piperine upon *Aspergillus parasiticus*. Natural Product Research 34(10): 1452-1455. *http://doi.org/10.1080/14786419.2018.1514395*

Caruso F, Mendoza L, Castro P, Cotoras M, Aguirre M, Matsuhiro B, Isaacs M, Rossi M, Viglianti A, Antonioletti R (2011). Antifungal activity of resveratrol against *Botrytis cinerea* is improved using 2-Furyl derivatives. PLoS One 6(10):25421. *https://doi.org/10.1371/journal.pone.0025421*

Chan MM-Y (2002). Antimicrobial effect of resveratrol on dermatophytes and bacterial pathogens of the skin. Biochemical pharmacology 63(2):99-104. *http://doi.org/10.1016/s0006-2952(01)00886-3*

Chang HT, Cheng YH, Wu CL, Chang ST, Chang TT, Su YC (2008). Antifungal activity of essential oil and its constituents from *Calocedrus macrolepis* var. *formosana*, florin leaf against plant pathogenic fungi. Bioresource Technology 99(14): 6266-6270. *https://doi.org/10.1016/j.biortech.2007.12.005*

Daglia M (2012). Polyphenols as antimicrobial agents. Current Opinion in Biotechnology 23:174-181. *https://doi.org/10.1016/j.copbio.2011.08.007*

De Campos MP, Chechinel FV, Da Silva RZ, Yunes RA, Zacchino S, Juarez S, Bella Cruz RC, and Bella Cruz A (2005). Evaluation of antifungal activity of *Piper solmsianum* C. DC. var. *solmsianum* (*Piperaceae*). Biological & Pharmaceutical Bulletin 28(8):1527-1530. *http://doi.org/10.1248/bpb.28.1527*

Díaz-Dellavalle P, Cabrera A, Alem D, Larrañaga P, Ferreira F, Dalla M (2011). Research: Antifungal activity of medicinal plant extracts against phytopathogenic fungus *Alternaria* spp. Chilean Journal of Agricultural Research 71(2):231-239. *http://doi.org/10.4067/s0718-58392011000200008*

Du Plooy W, Regnier T, Combrinck S (2009). Essential oil amended coatings as alternatives to synthetic fungicides in citrus postharvest management. Postharvest Biology and Technology 53(3):117-122. *https://doi.org/10.1016/j.postharvbio.2009.04.005*

Esserti S, Smaili A, Rifai LA, Koussa T, Makroum K, Belfaiza M, El Mostafa K, Faize L, Burgos L, Alburquerque N, Faize M (2017). Protective effect of three brown seaweed extracts against fungal and bacterial diseases of tomato. Journal of Applied Phycology 29:1081-1093. *https://doi.org/10.1007/s10811-016-0996-z*

Ezra D, Strobel GA (2003). Effect of substrate on the bioactivity of volatile antimicrobials produced by *Muscodor albus*. Plant Science 165:1229-1238. *https://doi.org/10.1016/S0168-9452(03)00330-3*

Fenical W, Sims JJ, Squatrito D, Wing RM, Radlick P (1973). Zonarol and isozonarol, fungitoxic hydroquinones from the brown seaweed *Dictyopteris zonarioides*. The Journal of Organic Chemistry 38:2383-2386. *https://doi.org/10.1021/jo00953a022*

Jasso de Rodríguez D, Trejo-González FA, Rodríguez-García R, Díaz- Jimenez MLV, Sáenz-Galindo A, Hernández-Castillo FD, Villarreal-Quintanilla JA, Peña-Ramos FM (2015). Antifungal activity *in vitro* of *Rhus muelleri* against *Fusarium oxysporum* f. sp. *lycopersici*. Industrial Crops and Products 75:150-158. *https://doi.org/10.1016/j.indcrop.2015.05.048*

Jiménez E, Dorta F, Medina C, Ramírez A, Ramírez I and Peña-Cortés H (2011). Anti-phytopathogenic activities of macro-algae extracts. Journal of Marine Drugs 9(5):739-756. *http://doi.org/10.3390/md9050739*

JIménez-Reyesa MF, Carrascob H, Oleab AF, Silva-Moreno E (2019). Natural compounds: a sustainable alternative to the phytopathogens control. Journal of the Chilean Chemical Society 64(2). *http://dx.doi.org/10.4067/S0717-97072019000204459*

Jun Jung H, Sang Sung W, Soo-Hwan Y, Soo Kim H, In-Seon L, Eun-Rhan W, Gun Lee D (2006). Antifungal effect of amentoflavone derived from *Selaginella tamariscina*. Archives of Pharmacal Research 29(9):746-751. *http://doi.org/10.1007/BF02974074*

Kabir F, Sultana MS, Kurnianta H (2015). Antimicrobial activities of grape (*Vitis vinifera* L.) pomace polyphenols as a source of naturally occurring bioactive components. African Journal of Biotechnology 14(26):2157-2161. *http://doi.org/10.5897/AJB2015.14617*

Khaleafa AF, Kharboush MAM, Metwalli A, Mohsen AF, Serwi A (1975). Antibiotic (fungicidal) action from extracts of some seaweeds. Botanica Marina 18:163-165. *https://doi.org/10.1515/botm.1975.18.3.163*

Kumar KA, Rengasamy R (2000). Evaluation of antibacterial potential of seaweeds occurring along the Coast of Tamil Nadu, India against the plant pathogenic bacterium *Xanthomonas oryzae* Pv. *oryzae* (Ishiyama) Dye. Botanica Marina 43:409-415. *https://doi.org/10.1515/BOT.2000.042*

Lacey LA, Neven LG (2006). The potential of the fungus, *Muscodor albus*, as a microbial control agent of potato tuber moth (Lepidoptera: Gelechiidae) in stored potatoes. Journal of Invertebrate Pathology 91:195-198. *https://doi.org/10.1016/j.jip.2006.01.002*

Lee SH, Chang KS, Su MS, Huang YS, Jang HD (2007). Effects of some Chinese medicinal plant extracts on five different fungi. Food Control 18:1547-1554. *https://doi.org/10.1016/j.foodcont.2006.12.005*

Martínez JA (2012). Natural fungicides obtained from plants. Chapter 1. In: Dhanasekaran D, Thajuddin N, Panneerselvam A (Eds). Fungicides for Plant and Animal Diseases 3-28. *https://doi.org/10.5772/26336*

Mazid M, Khan TA, Mohammad F (2011). Role of secondary metabolites in defense mechanisms of plants. Biology and Medicine 3:232-249.

Mendoza L, Cotoras M, Muñoz A, Yáñez K, Castro P, Aguirre M (2011). Fungitoxicity against *Botrytis cinerea* of a flavonoid isolated from *Pseudognaphalium robustum*. Molecules 16:3885-3895. *https://doi.org/10.3390/molecules16053885*

Mendoza L, Sepúlveda C, Melo R, Cotoras M (2015). Characterization of the antifungal activity against *Botrytis cinerea* of sclareol and 13-episclareol, two labdane-type diterpenoids. Journal of the Chilean Chemical Society 60(3):3024-3028. *http://dx.doi.org/10.4067/S0717-97072015000300010*

Mihaescu C, Neagu Frăsin LB (2020). The antifungal effect of some natural and synthetic chemical compounds on the bitter rot apple. AgroLife Scientific Journal 9(2):179-184.

Mihaescu C, Sturzeanu M, Din A (2021). *In vitro* evaluation of fungicide and bio-fungicides against isolates of *Alternaria solani* Sorauer. Romanian Biotechnological Letters 26(1):2295-2301. *https://doi.org/10.25083/rbl/26.1/2295.2301*

Mohamed SS, Saber AA (2019). Antifungal potential of the bioactive constituents in extracts of the mostly untapped brown seaweed *Hormophysa cuneiformis* from the Egyptian Coastal Waters. Egyptian Journal of Botany 59:695-708 *https://doi.org/10.21608/EJBO.2019.5516.1225*

Monsálvez M, Zapata N, Vargas M, Berti M, Bittner M, Hernández V (2010). Antifungal effects of n-hexane extract and essential oil of *Drimys winteri* bark against Take-All disease. Industrial Crops and Products 31: 239-244. *https://doi.org/10.1016/j.indcrop.2009.10.013*

Moreau J, Pesando D, Bernard P, Caram B, Pionnat JC (1988). Seasonal variations in the production of antifungal substances by some dictyotales (brown algae) from the French Mediterranean Coast. Hydrobiologia 162:157-162.

Muñoz-Concha D, Vogel H, Yunes R, Razmilic I, Bresciani L, Malheiros A (2007). Presence of polygodial and drimenol in *Drimys populations* from Chile. Biochemical Systematics and Ecology 35:434-438. *https://doi.org/10.1016/j.bse.2006.10.019*

Nahunnaro H and Bayaso I (2012). Inhibitory activity of plant extracts on the earlyblight pathogen *Alternaria solani* growth. Global journal of agricultural sciences 11(1):57-62. *http://dx.doi.org/10.4314/gjass.v11i1.10*

Parveen S, Hamid Wani A, Ali Ganie A, Ahmad Pala S and Ahmad Mir R (2014). Antifungal activity of some plant extracts on some pathogenic fungi. Archives of Phytopathology and Plant Protection 47(3):279-284. *https://doi.org/10.1080/03235408.2013.808857*

Ramaiah AK and Garampalli RKH (2015). *In vitro* antifungal activity of some plant extracts against *Fusarium oxysporum* f. sp. *lycopersici*. Asian Journal of Plant Science and Research 5(1):22-27.

Robles-Centeno PO, Ballantine DL, Gerwick WH (1996). Dynamics of antibacterial activity in three species of Caribbean marine algae as a function of habitat and life history. Hydrobiologia. 326:457-462.

Sanhueza L, Tello M, Vivanco M, Mendoza L, Wilkens M (2014). Relation between antibacterial activity against food transmitted pathogens and total phenolic compounds in grape pomace extracts from *Cabernet Sauvignon* and Syrah varieties. Journal of Advances in Microbiology 4:225-232. *https://doi.org/10.4236/aim.2014.45029*

Satish S, Mohana DC, Ranhavendra MP, Raveesha KA (2007). Antifungal activity of some plant extracts against important seed borne pathogens of *Aspergillus* sp. Journal of Agricultural Technology 3(1):109-119.

Schuster C, Konstantinidou-Doltsinis S, Schmitt A (2010). *Glycyrrhiza glabra* extract protects plants against important phytopathogenic fungi. Communications in Agricultural and Applied Biological Sciences 75(4):531-40.

Sempere-Ferre F, Asamar J, Castell V, Roselló J, Santamarina MP (2021). Evaluating the Antifungal Potential of Botanical Compounds to Control *Botryotinia fuckeliana* and *Rhizoctonia solani*. Molecules 26(9):2472. *https://doi.org/10.3390/molecules26092472*

Șesan TE, Enache E, Iacomi BM, Oprea M, Oancea F, Iacomi C (2015). Antifungal activity of some plant extracts against *Botrytis cinerea* Pers. in the blackcurrant crop (*Ribes nigrum* L.). Acta Scientiarum Polonorum Hortorum Cultus 14(1):29-43.

Shalini SKG, Akila R and Jayasekhar M (2019). Antifungal activity of plant extracts against *Diplocarpon rosae* causing black spot of rose. Journal of Pharmacognosy and Phytochemistry 8(3):3922-3924.

Sharifi-Rad J, Hoseini-Alfatemi SM, Sharifi-Rad M, Sharifi-Rad M, Iriti M, Sharifi-Rad M, Sharifi-Rad R and Raeisi S. (2015). Phytochemical compositions and biological activities of essential oil from *Xanthium strumarium* L. Molecules 20(4):7034-7047. *https://doi.org/10.3390/molecules20047034*

Shcherbakova L, Mikityuk O, Arslanova L, Stakheev A, Erokhin D, Zavriev S, Dzhavakhiya V (2021). Studying the ability of thymol to improve fungicidal effects of tebuconazole and difenoconazole against some plant pathogenic fungi in seed or foliar treatments. Frontiers in Microbiology 12:629429. *https://doi.org/10.3389/fmicb.2021.629429*

Singh AK, Pandey MB, Singh UP (2007). Antifungal activity of an alkaloid allosecurinine against some fungi. Mycobiology 35(2):62-64. *https://doi.org/10.4489/MYCO.2007.35.2.062*

Slusarenko AJ, Patel A, Portz D (2008). Control of plant diseases by natural products: Allicin from garlic as a case study. European Journal of Plant Pathology 121:313-322. *https://doi.org/10.1007/s10658-007-9232-7*

Soumya SL, Bindu RN (2012). Antifungal efficacy of *Capsicum frutescens* L. extracts against some prevalent fungal strains associated with groundnut storage. Journal of Agricultural Technology 8(2):739-750.

Stracquadanio C, Luz C, La Spada F, Meca G, Cacciola SO (2021). Inhibition of Mycotoxigenic Fungi in Different Vegetable Matrices by Extracts of Trichoderma Species. Journal of Fungi 7(6):445. *https://doi.org/10.3390/jof7060445*

Strobel GA, Kluck K, Hess WM, Sears J, Ezra D, Vargas PN (2007). *Muscodor albus* E-6, an endophyte of Guazuma ulmifolia making volatile antibiotics: isolation, characterization and experimental establishment in the host plant. Microbiology 153:2613-2620. *https://doi.org/10.1099/mic.0.2007/008912-0*

Ting-Ting W, Zhi-Hui C, Khan MA, Qing M, Ling H (2011). The inhibitive effects of garlic bulb crude extract on *Fulvia fulva* of tomato. Pakistan Journal of Botany. 43(5): 2575-2580.

Tripathi P, Dubey NK (2004). Exploitation of natural products as an alternative strategy to control postharvest fungal rotting of fruit and vegetables. Postharvest Biology and Technology 32(4):235-245. *https://doi.org/10.1016/j.postharvbio.2003.11.005*

Tripathi P, Dubey NK, Shukla AK (2008). Use of some essential oils as post-harvest botanical fungicides in the management of grey mould of grapes caused by *Botrytis cinerea*. World Journal of Microbiology and Biotechnology 24:39-46. *https://doi.org/10.1007/s11274-007-9435-2*

Trösken ER, Scholz K, Lutz RW, Völkel W, Zarn JA, Lutz WK (2004). Comparative assessment of the inhibition of recombinant human CYP19 (Aromatase) by azoles used in agriculture and as drugs for humans. Endocrine Research 30(3):387-394. *https://doi.org/10.1081/ERC-200035093*

Vicente TFL, Lemos MFL, Félix R, Valentão P, Félix C (2021). Marine Macroalgae, a Source of Natural Inhibitors of Fungal Phytopathogens. Journal of Fungi 7:1006. *https://doi.org/10.3390/jof7121006*

Worapong J, Strobel GA, Ford EJ, Li JY, Baird G, Hess WM (2001). *Muscodor albus* anam. Sp. *nov*., an endophyte from *Cinnamomum zeylanicum*. Mycotaxon 79:67-79.

Wu F, Jiaping C, Xiaodong Z, Qing L (2011). Thyme oil to control *Alternaria alternata in vitro* and *in vivo* as fumigant and contact treatments. Food Control 22:78-81. *https://doi.org/10.1016/j.foodcont.2010.05.010*

Xie Y, Wang Z, Huan Q, Zhan D (2017). Antifungal activity of several essential oils and major components against wood-rot fungi. Industrial Crops and Products 108:278-285. *https://doi.org/10.1016/j.indcrop.2017.06.041*

Yilar M and Bayar Y (2018). Antifungal activity of *Thymbra spicata* L. and *Rosmarinus officinalis* L. essential oils against *Monilinia fructigena* Honey in Whetze. Türk Tarım ve Doğa Bilimleri Dergisi 5(2):121-126. *https://doi.org/10.30910/turkjans.421344*

Zarins I, Daugavietis M, Halimona J (2009). Biological activity of plant extracts and their application as ecologically harmless biopesticide. Sodininkystė ir Daržininkystė 28(3):269-280.

Zhang Z, Yang, T, Mi N, Wang Y, Li G, Wang L, Xie Y (2016). Antifungal activity of monoterpenes against wood white-rot fungi. International Biodeterioration & Biodegradation 106:157-160. *https://doi.org/10.1016/j.ibiod.2015.10.018*