More insights into approaches with potential effect against pathogenic *Fusarium* species

*Abdeslam Jaafari and Souad Lekchiri

Laboratory of Biological Engineering, Faculty of Sciences and Technologies, Sultan Moulay Slimane University, BP 523, Mghila, 40000, Beni Méllal, Morocco
*Corresponding author's email: *abdeslamjaafari@gmail.com*

Abstract

Fusarim species are a group of pathogenic fungi responsible for different plant diseases as well as damage of stored products like banana, rice and cereals. They are characterized by a widspread distribution because of their capacity to grow in different substrates. Against these pathogenic fungi, many approachs have been tried to protect crops and stored products from their devastating effects. Chemical molecules are widely used for their effective activity as fungicides, but they may cause important damage to crops, human and environment. For this reason, researchers are trying to find an alternative allowing the farmer to ovoid these negative effects of chemical fungicides. Among these potential alternatives, we find the use of natural products (monoterpenes, flavonoids etc), plant extracts (including essential oils), biological control agents (bacteria and fungi), antimicrobial nanomaterials and approachs aiming to improve plant resitance and defence.

Keywords: Control, Disease, Fusarium, Resistance, Treatment.

Introduction

Fusarium is a fungal genus belonging to the family of Nectriaceae. Species of this genus are hyaline filamentous fungi characterized by their cosmopolitain distrubion. They can be found in soil, in plant roots and aerial parts, in plant debris and other organic substrates (Nelson *et al.,* 1994; Lombard *et al*., 2015). Their capacity to grow in many different substrates and the fact that they have developped excellent mechanisms for dispersal may explain their widspread distribution. Fusarium species are known to cause many plant diseases like crown rot, head blight, scabon cereal grains, vascular wilts on a wide range of horticultural crops; root rots, cankers and other diseases such as pokkah-boeng on sugarcane and bakanae disease of rice (Asam *et al.,* 2017). Fusarium species also cause many human and animal diseases because of the mycotoxins they can produce such as fumonisins, trichothecenes and zearalenone (Nesvorna *et al.* 2012; Broyde and Dore, 2013). In addition, species of Fusarium can be responsible for damage of stored products like cereals, rice and many other crops (Nesvorna *et al.,* 2012).

One of the most pathogenic fungus devastating plants is *Fusarium oxysporum* f. sp. *albedinis*. It is responsible for vascular wilt of date palm (*Phoenix dactylifera*) known under the name of Bayoud disease. The Bayoud is the most important disease of date palm in Morocco and around the world. It has destroyed about 60% of Moroccan palm plantations causing economical, ecological and social damages (El Modafar, 2010). It attacks the plant through roots and then spreads in other parts of the tree by vascular system leading to foliar withering and death of palm trees (El Modafar, 2010; Saleh *et al.,* 2017). Its transmission and surviving under adverse environmental conditions are related to its typical micro and macroconidia, as well as chlamydospores it can produce. The releases of propagules ensure dissemination of the fungus through infested soil, irrigation water and infected date palm tissues. Chemical, prophylactics, genetics and biological controls have been tried in order to reduce the dissemination of this fungal disease but without hoped results (Momma *et al.,* 2010). *Fusarium solani* is responsible for wilt and rot diseases in different tree species including *Erythrina suberosa* and *Delbergia sissoo* (Javaid *et al.,* 2005; Bajwa *et al.,* 2003 a, b).

Fusarium moniliforme is an endophytic fungus attacking maize by the production of mycotoxin called fumonisin (FB1 and FB2). Clonal infection of seeds and plant debris are the means of the fungal transmission (Ketabchi and Shahrtach, 2011). Likewise, *Fusarium thapsinum* causes stalk rot in maize (Tahir *et al.,* 2018). Tomato is among plants affected by *Fusarium oxysporum* f. sp. *lycopersici* (Khurshid *et al.,* 2014, 2016). It causes one of the most damaging tomato diseases leading to important losses (Ojha and Chatterjee, 2012). This fungus can infest tomato crops via contaminated seeds (Reis and Boiteux, 2007). Sweet potato is also a plant infected by *Fusarium oxyporum* f. sp. *batatas*. This fungal infection of sweet potato is characterized essentialy by wilting and leaf yellowing. Browning of vascular tissues in the lower stems is also observed in infected plants (Thompson *et al.,* 2011). Fusarium wilt is a damaging disease of cotton responsible for important losses in cotton-producing countries like Australia, USA, Egypt, Tanzania and China (Abd-Elsalam *et al.,* 2014). This disease is caused by *F. oxysporum* f. sp. *vasinfectum* that reduces cotton production by about 100,000 bales per year in the USA (Davis *et al.,* 2006). Another davastating fungal infection is banana fusariosis caused by *F. oxysporum* f. sp. *cubense.* This disease is responsible for significant losses in coutries like Ivory coast, is characterized by an uniform and deadly yellowing of banana leaves (Kobert *et al.,* 2017). Lentil also can be attacked by a Fusarium species called *F. oxysporum* f. sp. *lentis* causing a disease charachterized by stunting, wilting and reduction of root system. It has been reported also that internal vascular discoloration of the lower stem is an important symptom observed in infected lentil (Hiremani and Dubey, 2019). In the summer of 1999-2000, a severe losses of lentil seedings contaminated by this fungus occured in Italy (Tosi and Cappeli, 2001).

Many other damaging plant diseases are caused by *Fusarium* species. Sugarcane wilt by *Fusarium sacchari*, Bakanae in rice by *Fusarium fujikuroi*, flowering malformation of mango by *Fusarium manginifera*, green point gall of cacao by *Fusarium decemcellulare*, oil palm wilt by *F. oxysporum* f. sp. *elaeidis*, crown rot by *Fusarium pallidoroseum*, Panama disease by *F. oxysporum* f. sp. *cubensis*, Gibberella zeae by *Fusarium graminearum,* Papaya internal fruit rot by *Fusarium* spp., pitch caner in pine by *Fusarium circinatum,* Corm rot of gladiolus by *F. oxysporum* f. sp. *gladioli,* basal rot of onion caused by *F. oxysporum* f. sp. *cepae* and Fusarium wilt of *Washingtonia robusta* by *F. oxysporum* f. sp. *palmarum* (Khan *et al.,* 2010; Riaz *et al.,* 2010; Giesbrech *et al.* 2013; Javaid and Akhtar, 2015; Slinski *et al*., 2015; Omar *et al.* 2018; Million *et al.* 2019; Scherm *et al.*, 2019).

The aim of this review is to presente several approachs with a potential effect against some plant diseases caused by different *Fusarium* species. The species of Fusarium genus have a lot of communes points related to their structure, physiology and mode of infection. Therefore, when an approach, or product, shows an effect on a specific species, it could be interesting to test it against another species. The approaches discussed in this review are related to treatment by natural and synthesized molecules, treatment by plant extracts and essential oils, biological control, nanoparticles and methods used to enhance plant resistance.

Use of natural products

Natural products, extracted from plants or microorganisms, are widely used for their diverse biological properties such as antibacterial, antifungal, herbicidal, anticancer and antioxidant activities (Khan and Javaid, 2019, 2020; Javaid *et al.,* 2020; Javed *et al.,* 2021). It has been shown in many studies that microorganisms and plants are able to produce chemical molecules or hormones that they use for their defence against other microorganisms. Sometimes, these molecules are used as template to synthesize analogues having the same activities (Ntie-Kang, 2016; Sunil and Hoskins, 2017). Many classes of natural compounds have been studied for their potential effect against *Fusarium* species.

Monoterpenes: Monoterpenes, classified into monoterpene hydrocarbons and oxygenated monoterpenes, are the main constituents of the majority of plant essential oils. It has been reported that this class possess an important insecticidal, herbicidal, fungicidal and bactericidal properties (Caravon *et al*., 2014; Karlsson *et al.,* 2017; Ghasemi *et al.,* 2020). Twelve monoterpenes namely camphene, camphor, carvone, 1,8-cineole, cuminaldehyde, fenchone, geraniol, limonene, linalool, menthol, myrcene and thymol were tested against four plant pathogenic fungi including *F. oxysporum*. The study was performed using mycelial growth inhibitory technique. Results reported that thymol, (S)-limonene and 1,8-cineole have antifungal effect on the tested fungi, and thymol was the most active against *F. oxysporum* with EC_{50} of 50.35 mg mL^{-1}. The same study reported that thymol acted by inhibiting pectin methyl esterase and cellulase of tested fungi (Marei *et al*., 2012).

Flavonoids: Flavonoïds, secondary metabolites generaly located in plant leaves, are not only a constitutive agents but they also play an important role in plant defence against microbs (Kanwal *et al.,* 2010; Mathesius, 2018; Laila, 2020; Bilska *et al.,* 2018). Several flavonoids glycosides isolated from carnation (*Dianthus caryophyllus*) were found antifungal against different pathotypes of *F. oxysporum* f. sp. *dianthi* (Galeotti *et al.*, 2008). Extract of barley were tested against *Fusarium poae, F. culmorum* and *F. graminearum*, and the result revealed that the flavonoid dihydroquercetin was a strong inhibitor of *Fusarium* growth and macrospore formation (Skadhauge *et al.,* 1997; Bollina *et al.*, 2011). *In vitro* effect of an extract enriched in flavonoids obtained from *Triguero asparagus,* was checked on *Fusarium* species pathogenic to asparagus, carnation and strawberry. A significant inhibition of mycelial growth and sporulation of *F. oxysporum* f. sp. *asparagi, F. oxysporum* f. sp. *dianthi* and *Fusarium* sp. pathogenic to stawbery was observed without affecting plant safety (Rozado-Alvares *et al.,* 2014). Strains of *Fusarium culmorum* and *F. graminearum* were incubated *in vitro* with flavonoids which are usually produced by cereals in response to fungal infections. Results showed that mycotoxin production by the two fungi was significantly reduced by luteolin, kaempferol, naringenin and apigenin. The same study also established a relationship between antifungal effect of flavonoids and their antioxidant and antiradical properties (Bilska *et al.,* 2018).

Alkaloids: An alkaloid extracted from *Prosopis juliflora* (weed plant) was evaluated for its antifungal effect on toxigenic and non-toxigenic *Fusarium verticillioides* isolated from seeds of paddy, maize and sorghum. Compared to some conventional fungicides (copper oxychloride, thiophanate-methyl, chlorothalonil and carbendazim), it has been shown that this natural alkaloid was the most effective at low concentration (300 µg mL^{-1}) than those chemical fungicides which were effective only at hight concentrations (2000 µg mL^{-1}) (Deepa *et al.,* 2012). Some new saturated pyrrolizidine monoester alkaloids, 3-acetyltrachelanthamine, floridine, floridinine and floridimine, heliovicine were isolated from *Heliotropium joridum* and their biological activity revealed that 3-acetyltrachelanthamine and floridine have the most important effect against *Fusarium monoliforme* (Reina *et al.,* 1997). Besides monoterpenes, flavonoids and alkaloids, it has been reported in the literature that other classes of natural products such as polyphenols, tanins, saponins and sterols have a significant antifungal effect against some pathogenic *Fusarium* species (Rodriguez *et al.,* 2012; Isidore *et al*., 2018).

Eugenol: It has been shown that small concentrations of eugenol, pure product extracted from clove, is able to induce the destruction of structure of *Fusarium oxysporum* f. sp. *vasinfectum* (Abd-Assalam and Khokhlov, 2015). Eugenol also showed toxicity against other pathogenic fungi (Morcia *et al.,* 2012; Matan *et al.,* 2014). Because of its lipophilic character, eugenol pass easly through cell membrane (Bakkali *et al.,* 2008). Its mechanism of action may be related to the iactivation of enzymes, altering fluidity and permeability of cell membrane or disturb the genetic material (Braga *et al*., 2007; Woo *et al.,* 2009). Mechanism of action of eugenol can also involve ergosterol biosynthesis inhibition (de Oliveira *et al.,* 2013).

Alphapinene and betacaryophylene: These are the major components of *Chromolaena odorata* leaf extracts. These two molecules exhibited antifungal acticvities against *Fusarium* species and several other fungi (Ling *et al*., 2003 ; Noudogbessi *et al.*, 2008).

Use of synthesized molecules

In addition to natural molecules, synthesized molecules, with less negative effect on crops and environment, are also studied for their potential activity on pathogenic *Fusarium* species. Diphenyl diselenide and some of its synthetic analogues were evaluated *in vitro* for their antifungal activity against 116 strains of pathogenic fungi, including *Fusarium* species. The compounds showed antifungal activity against some pathogenic *Fusarium* species with inhibitory activity of 2–16 µg mL^{-1} and minimum fungicidal oncentration of 4–64 µg mL^{-1} (Loreto *et al.,* 2011). In another study, some benzimidazoles, aromatic hydrocarbons and sterol biosynthesis inhibitors showed a significant activity to prevent or control pathogenic *Fusarium* spp. growth (Daferera *et al.,* 2003). Furthermore, five substituted flavones and their mixtures with unsubstituted flavone or flavanone were evaluated for their antifungal activity against five *Fusarium* spp. Among these molecules, 4′-methylflavone and 2′,6′-dichloroflavone showed the most important effect. The difference observed in the molecules activity were found related to their chemical structure (Silva *et al.,* 1998).

Use of essential oils and plant extracts

There is an increasing interest in the use of essential oils for their biological activity (Ferdosi *et al.,* 2020, 2021). Because of their safty, they are considered as an alternative to chemical agents which are toxic for both plants, human and environment (Tepe *et al.,* 2005; Srenivasa *et al.,* 2011; Naz *et al.,* 2014).

In an interesting study, essential oils of clove (*Syzygium aromaticum*), lemongrass (*Cymbopogon citratus*), mint (*Mentha piperita*) and eucalyptus (*Eucalyptus globulus*) were tested against *F. oxysporum* f. sp. *lycopersici* 1322. All the tested essential oils showed an inhibitory effect on the fungal growth in dose-dependent way. The most active was clove essential oil showing complete inhibition of mycelial growth (MIC = 31.25 ppm and IC_{50} = 18.2) and inhibition of spore germination (0.3 ppm). The other essential oils (lemongrass, mint and eucalyptus) were also active but at higher concentrations. GC-MS analysis showed that the major components of clove essential oil were eugenol (75.41%), E-caryophyllene (15.11%) and α-humulene (3.78%). Results of the same study, using scanning electron microscopy and atomic force microscopy, showed shrivelled hyphae and disrupted spores in clove essential oil treated samples. Taken together, these results suggested that clove essential oil could be used as biofungicide for the control of *F. oxysporum* f. sp. *lycopersici* (Sharma *et al.*, 2017). In another study, essential oils of many plants like eucalyptus, clove, cedar wood, citronella and neem showed antifungal activities against nine *Fusarium* species at concentrations of 500–2500 ppm. Among the tested essential oils, that of citronella had the highest inibitory effect against *F. oxysporum* (Sreenivasa *et al.,* 2011). In Brazil, important losses in *Piper nigrum* cultivation are caused by *F. solani* f. sp. *piperis*. Essential oil of *Piper divaricatum,* with methyleugenol (75%) and eugenol (10%) as major constituents, was tested at concentrations of 0.25 to 2.5 mg mL^{-1} against this fungus. Results reported that the essential oil had a strong antifungal index (18% to 100%). The same study, using 3D structure of the β-glucosidase from *Fusarium solani* f. sp. *piperis*, showed that β-glucosidase residues were srongly involved in protein-engenol/methyleugenol interaction, explaining the antifungal action of these two phenylpropenes against the pathogenic fungus (Da Silva, 2014).

Fusarium culmorum and *Fusarium verticillioides* are two fungi of stored rice mycobiota. Essential oils of bay leaf, cinnamon, clove and oregano were tested against these fungi, *in vitro* and *in vivo*, and they showed significant control of fungal growth. In the *in vitro* test, oregano essential oil was the most effective (100% inhibiting growth). The other essential oils (bay leaf, cinnamon, clove) also showed marked effect as they reduced fungal growth by 90%. GC-MS analysis of these essential oils revealed that they are rich in oxygenated molecules: 92% in cinnamon (eugenol 60% and eugenyl acetate 18.3%), 90.3% in clove (eugenol 89.8%), 78.8% in bay leaf (eucalyptol 51%) and 71.8% in oregano (carvacrol 49.6% and thymol 21.2%). The content of monoterpenes and sesquiterpenes were 18%, 9%, 5% and 25% in bay leaf, clove, cinnamon and oregano, respectively (Rosello *et al*., 2015). Essential oil of mexican oregano (*Lippia berlandieri*) was found a potential inhibitor of *F. oxysporum* with MIC of 0.15 $\mu L\ mL^{-1}$ and totally inhibited the fungal biomass production at 0.2 $\mu L\ mL^{-1}$. When tested on infected tomato seeds, oregano essential oil at 0.5% completely inhibits the fungus proliferation without affecting seed germination rates (Cueto-Wong *et al.*, 2010). Essential oils of origanum (*Origanum onites*), lavender (*Lavandula stoechas* subsp. *stoechas*), fennel (*Foeniculum vulgare*), laurel (*Laurus nobilis* L.) and myrtle (*Myrtus communis*) markedly suppressed mycelial growth and spore germination of *F. oxysporum* f. sp. *radicis-cucumerinum* causing root and stem rot of cucumber (Soylu and Incecara, 2017). Essential oils of *Rosmarinus officinalis* and *Salvia officinalis* showed pronounced effect against pathogenic *Fusarium* species (Mekonnen *et al.,* 2019).

Plant extracts prepared in different solvents (ethanol, acetone, methanol, ethyle acetat etc) have been studied for various biological activities. Ethanolic and aqueous extracts from leaves of six plants were evaluated for their antifungal activity against *Fusarium* sp. The study reported that ethanolic extracts were more effectives than aqueous ones. Chemical analysis revealed that polyphenols, flavonoids, polyterpenes, sterols and tannins could be responsible for antifungal activity of these ethanolic extracts (Isidore *et al.,* 2018). Aqueous and alcoholic extracts of *Acacia farnesiana* were tested against *F. oxysporum* f. sp. *lycopersici*. Results showed an important percentage of inhibition of mycelial growth (> 90% after 72 h). This antifungal effect was related to flavonoids, tannins, phenols, alkaloids and saponins present in the extracts (Rodrigez Pedroso *et al.,* 2012). Furthermore, aqueous and different solvent extracts from *Prosopis juliflora* (weed plant) had a significant fungitoxicity against all the strains of toxigenic and non-toxigenic *Fusarium verticillioides* isolated from seeds of paddy, maize and sorghum (Deepa *et al.,* 2012). Other plant extracts like *Chromolaena odorata* showed marked activity against *Fusarium* species (Kra *et al.,* 2009). It has been shown that aqueous extracts from fresh aerial parts of four plant species (*Artemisia herba-alba, Cotula cinerea, Asphodelus tenuifolius* and *Euphorbia guyoniana*) could inhibit *Fusarium graminearum* and *Fusarium sporotrichioides* growth. The activity of these extracts was related to their tannins, flavonoids, saponins, steroids and alkaloids (Salhi *et al.,* 2017).

In a study, 131 extracts, resins, oils and mother tinctures from 63 plants were evaluated for their potential activity against *Fusarium guttiforme* using plate-hole method. On the other hand, mother tinctures were tested for their capacity to control pineapple fusariosis in situ. Results showed that mother tinctures of *Glycyrrhiza glabra, Myroxylon balsamum, Aloe vera* and *Allium sativum,* resin of *Protium heptaphyllum* and crude extracts of *Rhizophora mangle*, exhibited significant antifungal effects against *Fusarium guttiforme* (Costa *et al.*, 2016). Several plant extracts were evaluated for their effect on soil infested with *F. oxysporum* f. sp. *chrysanthemi*. The results showed that aqueous emulsions (10%) of pepper/mustard, cassia and clove extracts reduced the fungal population density by 99.9, 96.1 and 97.5%, respectively, after 3 days (Bowers and Locke, 2000). Khurshid *et al.* (2018) reported that methanolic extract of aerial parts of an allelopathic grass *Cenchrus pennisetiformis* and its various organic solvent fractions showed pronounced antifungal activity against *F. oxysporum* f. sp. *lycopersici*. They further reported that soil amendment with dry biomass of this grass significantly reduced disease incidence in tomato plants. Likewise, methanolic extract of *Coronopus didymus* significantly inhibited the growth of *Fusarium moniliforme* (Javaid *et al.,* 2018). Aftab *et al.* (2019) reported that methanolic extract of vegetative parts of *Nigella sativa* can significantly suppress the growth of *F. oxysporum.* Shoot extracts of *Sisymbrium irio* contain potent antifungal compounds namely, β-sitosterol and fatty acid methyl esters against *Fusarium oxysporum* f. sp. *cepae* (Akhtar *et al.,* 2020). Similarly, leaf extract of *Chenopodium murale* contains many antifungal compounds for the control of *F. oxysporum* f. sp. *lycopersici* and *F. oxysporum* f. sp. *cepae* (Naqvi *et al.,* 2019; Nawaz *et al.,* 2020).

Biological control of *Fusarium* spp.

Intensive application of chemical antifungal has lead to an increased negative impacts on plants, human, soil flora and environment. Therefore, biological control could be an excellent alternative of the chemical treatment. Biological control of fungal diseases is based on the use of microorganisms to fight pathogenic fungi responsible for diseases. Against Fusarium species, many bacteria and fungi were tested. Rhizobacteria, especialy actinmycetes and *Pseudomonas* sp, are among the microorganisms mostly used in the field of biological control.

Actinomycètes: Rhizospheric actinomycetes represent excellent candidates in biological control of fungal diseases. In fact, 60% of natural antifungals used in agriculture are derived from the actinomycete genus *Sytreptomyces* (Bubici, 2018). Because of their abundance in the natural soil and plant roots, they are frenquetly used as biological control agents (Aichour *et al.*, 2012). Several biocontrol trials using Streptomycetes were conducted against four payhogenic *Fusarium* species namely *F. fujikuroi, F. graminearum, F. solani* and *F. oxysporum*. Results showed marked Fusarium wilts reduction of 0–50%. Yekkour *et al.* (2012) reported the capability of the 133 strains of filamentous actinomycetes to inhibit growth of different *Fusarium* species (Yekkour *et al*., 2012). In a study carried out under field conditions, cucumber wilt caused by *F. oxysporum* f. sp. *cucumerinum* was treated by a suspension of *Streptomyces albospinus* CT205 spore. It has been shown that this treatment reduced pathogenic effect by 22% and plant death by 33%. Also, the numbers of *Fusarium* colony forming units was significantly decreased and the microbial structure in rhizosphere was improved (Wang *et al.,* 2016). *Actinomadura* strain AC170 isolated from saharian palm was evaluated for its antifungal activity against severel pathogenic and toxigenic fungi. Results showed that butanolic extract of this bacteria had an important antifungal effect against the all tested fungal strains. This activity was related to an aromatic compound present in this extract (Badji *et al.,* 2005). It has been reported in other study that five strains of *Streptomyces* spp. (CAI-24, CAI-121, CAI-127, KAI-32 and KAI-90) isolated from herbal vermicomposts showed remarkable control effects against *F. oxysporum* f. sp. *ciceris* (Gopalakrishnan *et al.,* 2011). The biocontrol mechanisms of *Streptomyces* spp. would be assured by their chitinolytic activity, endophytic trait, volatil organic molecules production and plant resistance induction (Bubici, 2018).

Pseudomonas**:** *Pseudomonas* is a genus of gram-negative bacteria from Pseudomonadaceae family that counts about 191 described species (Meghdas *et al.,* 2004). This genus is among the bacteria mostly used in biological control of plants diseases (Sharf *et al.,* 2021). Tested against some fungi including *F. oxysporum*, several strains of *Pseudomonas* showed an important growth inhibiton effect (Sindhu *et al.,* 1999). These bacteria are excellent competitors vis à vis fungal and bacterian microflora in the soil. They have a short generation time *in situ* and are able to use plants exudates as nutrients and chelate iron ions by the production of siderophores like pyoverdine (Aichour *et al.*, 2012). *Pseudomonas* effect is due to the production of many secondary metabolites like phenazines, phloroglucinols, pyoluteorine, pyrrolnitrine, lipopeptides and hydrogen cyanure. *Pseudomonas fluorescens* is considered as the most important species of this genus because of its capability to produce different plants growth factors and bioactive molecules necessary to plant proteciton (Aichour *et al.,* 2012).

Bacillus**:** *Bacillus* is another genus of gram-positive bacteria genus with interesting prpreties as agent of biological control of fungal diseaeses. Two species of this genus have been studied is this sense. *Bacillus cereus* is responsable of foodborne intoxiations. It has been reported that methanol extract of *Bacillus cereus X16* inhibits the mycelial growth of *Fusarium roseum* var. *sambucinum*, *in vitro* and *in vivo*. The extract, made in the interaction region between fungal and host, contains many antifungal molecules (Sadfi *et al.,* 2002). *Bacillus subtilis* is an endophytic bacterium with an important effect in biological control of *Fusarium moniliforme*. This bacteria can reduce mycotoxin accumulation during the fungus growth phase. This bacterium is interesting since it is considered as an ecological homologue to *F. moniliforme* because it occupies the identical ecological niche within the plant (Bacon *et al.,* 2001).

Other bacterial isolates: Date palm is being destroyed by bayoud disease caused by *F. oxysporum* f. sp. *albedinis*. Isolates belonging to 21 bacteria including *Bacillus* spp., *Rhizobium* spp., *Ulocladium atrum, Candida guilliermondii, Pseudomonas* sp., *Rahnella aquatilis* and other bacteria, were evaluated for their effects on the mycelial growth and the sporulation of this pathogenic fungus. Results showed that *B. pumilus* W1, *R. aquatilis* W2 and *B. cereus* X16 inhibited the mycelial growth and sporulation of *F. oxysporum* f. sp. *albedinis* by 70–77% and 80–95%, respectively (El Hassni *et al.*, 2007).

Endophytic and other biocontrol fungi: Beside bacteria, some fungi, in particular endophytic fungi, have shown an excellent effect as agent of biological control against plants diseases. In a recent study, 30 endophytic fungal species have been isolated from different Chineese plants and evaluated for their effect against *F. oxysporum* f. sp. *cucumerinum*, causing wilt in cucumber. The test was performed using *in vitro* dual culture assay. The results reported that the 30 endophytic fungal isolates have important inhibiting effects on the mycelial colony growth of *F. oxysporum* f. sp. *cucumerinum* (> 66%) compared to control. The most effective isolates were those of *Penicillium* sp., *Guignard*ia *mangiferae, Hypocrea* sp., *Neurospora* sp., *Eupenicillium javanicum,* and *Lasiodiplodia theobromae*. Greenhouse test showed that the most effective fungi suppressed wilt severity when co-inoculation with pathogen *F. oxysporum* f. sp. *cucumerinum*. Furthermore, the same study reported that these isolates increased plant height, aerial fresh and dry weight of host plant (Abro *et al.*, 2019). Other study showed that species of genus *Trichoderma,* belonging to Hypocreaceae family, can be used as antagonistic in biological control of several soil-borne pathogens (Hanson and Howell 2004; Bajwa *et al.*, 2004). Five species of *Trichoderma* were tested *in vitro* for their antagonist effect againts *F. oxysporum* causing wilt disease in sweet peppers. The results showed that *T. viride* had the best effect followed by *T. harzianum, T. aureoviride, T. koningii* and *T. pseudokoningii*. These species reduced colony growth of pathogenic fungus by 62, 36, 24, 18 and 6%, respectively (Sahi and Khalid, 2007). *Trichoderma* species also have potential to control postharvest growth and toxin production by *Fusarium monilifome* (Bacon *et al.* 2001). There are also reports of control of *Fusarium solani, F. oxysporum* f. sp. *Cepae* and *F. oxysporum* f. sp. *lycopersici* by *Trichoderma harzianum* (Mukhtar *et al.,* 2006; Javaid *et al.,* 2014; Akhtar and Javaid, 2018)

Use of nanomaterials for control of *Fasarium* spp.

Efficient and ecosafe techniques to administrate inssticides, herbicides, fungicides and fertilizers are needed in order to protect consumers, plants and environment (Li *et al.,* 2007; Gogoi *et al.,* 2009). Biobased nanomaterials is one of these promising methods which could improve protocols to fight against plant diseases (Abd-Elsalam and Khokhlov, 2015 ; Um-e-Aiman *et al.,* 2021). It has been reported that nanobiocid, composed by biobased chemicals, are able to eliminate the causal agent of rice blast disease (Gogoi *et al.,* 2009).

Regarding *Fusarium* genus, different concentrations of eugenol oil nanoemulsions (EON) were tested against *F. oxysporum* f. sp. *vasinfectum* both *in vitro* and *in vivo.* Analysis of total proteins isolated from the fungus before and after treatmet with EON was performed by SDS-PAGE. The results indicated that there was a decrease in extracellular soluble small molecular proteins. Also, light micrographs showed mycelia and spores treated with EON indicating the destruction of fungal structure (Abd-Assalam and Khokhlov, 2015). Toxicity of EON molecules on cotton plants was evaluated by studying viability on 10 cotton genotypes. It has been shown that only high concentration (10%) of emulsion, when used for *Fusrium* control in muskmelon, caused stunting and other phytotoxic symptoms (Morcia *et al.,* 2012; Bowers and Locke, 2000). Another study was carried out to evaluate the effect of silver nanoparticles (AgNPs) on *F. oxysporum*. Results showed that silver nanoparticles reduced colony formation of *F. oxysporum* in dose dependent manner. A concentration of 5000 ppm of AgNPs decreased colony formation to 35%, 27% and 24% after 1, 2 and 3 hours of exposure, respectively. Also, fungal colony formation is reduced by extended spore exposure to silver nanoparticles (Abkhoo and Panjehkeh, 2017).

A study comparing chitosan (CS) and chitosan nanoparticles (CS/NPs) was conducted against *Fusarium graminearum* causing head blight on wheat. Technique used for CS/NPs preparation was based on the ionic gelation of CS with tripolyphosphate with centrifugation and pH modification. Different CS/NPs were prepared based on particle diameter and molecular weights. Results showed that fungal growth reduction, at concentrations of 1000 and 5000 ppm, was 68.18% and 77.5% for CS and its NPs, respectively (Kheiri *et al.,* 2017). Taken together, these results suggest that CS and NPs can be used as agents of crop protection. In greenhouse trials, concerning disease progress at 28 days after inoculation (dpi), the area under curve was 7.36 and 7.7 for control plants treated with aqueous solution of acetic acid and distilled water, respectively. On the other hand, plants treated with CS and NPs had approximately 3.61 and 3.34, respectively (Kheiri *et al.*, 2017).

Approachs providing plant resistance against *Fusarium* spp.

Enhancing plant resistance is a promising approach to fight diseases. It is based on inducing systemic resistance by employing different technics like localized pretreatment with elicitors (Hammerschmidt *et al.,* 2001) or application of microrganisms isolates (El Hassni *et al.,* 2004). Molecules provinding plant resistance may be secreted by microrganism membrane. It's the case of lipopolysaccharids (Reitz *et al.,* 2000), N-acétylchitooligosaccharids (Yamagushi *et al.,* 2000) or glycoproteins (Lepoivre and Semal, 1989). Also, inductor oligosaccharides may be produced by a membrane of host cells under bacterial or fungal enzymatic reaction (Lepoivre and Semal, 1993). Once in contact with plants, elicitors cause the expression of biochemical changes involved in defence responses induction. Such biochemical reactions include activation of various defence-related enzymes, accumulation of active oxygen species and synthesis of pathogenesis-related proteins and phytoalexins (Nurnberger and Lipka, 2005). Jasmonic acid (JA) is among elicitors which has been studied for its potential effect against *F. oxysporum* f. sp. *albedinis* causing bayoud (date palm disease). It is a natural phytohormone involved in plant development (Creelaman and Mullet, 1997). The aim of the study was to evaluate the effect of this elicitor on two enzymes peroxidases and polyphenoloxidases involved in plant defence . Results reported that the activity of the two enzymes *viz.* was increased by exogenous application of Jasmonic acid at 50 mM compared to untreated plants. Also, chromatographic analysis by PAGE showed an inmportant band intensity ralated to the major peroxidases and polyphenoloxidases isoforms in seedlings treated by both jasmonic acid and the fungus. Examination of plants showed a limited necrotic lesions in asymptomatic plants compared to symptomatic ones. All these results indicated that the elicitor jasmonic acid xcould enhance date palm resistance to this pathogen by a mechanism involving the activation of enzymes like peroxidases and polyphenoloxidases (Jaiti *et al.,* 2009). Another study trying to enhance date palm resistance against bayoud disease was conducted by El Hassni *et al.* (2004). It consisted in the pretreatment of date palm seedlings with an hypoaggressive *F. oxysporum* f. sp. *albedinis* isolate. Results showed that this isolate protected date palm against further infection by the pathogen. The hight level of phenolics and peroxidase activity, involved in date palm resistance to *F. oxysporum* f. sp. *albedinis* indicate the ability of pretreated date palm to establish a faster defence response in its roots. Also, height level of non-constitutive hydroxycinnamic acid derivatives and constitutive caffeoylshikimic acids was observed in pretreated plants. These constituents are known to play an mportant role in date palm defence against *F. oxysporum* f. sp. *albedinis* (El Hassni *et al.,* 2004). Another study of the same team reported that application of bacterial isolates into date palm seedings improved its defence reactions. These reactions evaluated by non-constitutive hydroxycinnamic acid derivatives and sinapic derivative amounts. It has been shown, in the same study, that resitance reaction was more pronounced in resistant cultivar compared to the sensitive one (El Hassni *et al.,* 2007). *Fusarium oxysporum* f. sp. *lentis* MR84 is another Fusarium species responsible of lentil disease. It has been reported that culture filtrate of *Trichoderma harzianum* T-ADS protected totally lentil plants against infection by this pathogenic fungus without interaction between the two fungi, which suggests that *Trichoderma harzianum* T-ADS acted by enhancing plant resistance (Essalmani and Lahlou, 2004).

Table 1: Approaches with potential effect against *Fusarium* species.

Approach	Examples
Natural products	**Monoterpens**: camphene, carvone, cineol, linalool… **Flavonoids**: by luteolin, kaempferol, naringenin and apigenin… **Alkaloids:** pyrrolizidine monoester alkaloids, 3'-acetyltrachelanthamine, floridine, floridinine and floridimine, heliovicine… **Eugenol** **Alphapinene and betacaryophylene**
Synthesized molecules	Diphenyl diselenide Benzimidazoles Aromatic hydrocarbons Substituted flavones : 4′-methylflavone and 2′,6′-dichloroflavone
Essential oils and plant extracts	Essential oils of clove (*Syzygium aromaticum*), lemongrass (*Cymbopogon citratus*), mint (*Mentha piperita*) and eucalyptus (*Eucalyptus globulus*) Aqueous extracts from fresh aerial parts of four plant species (*Artemisia herba-alba, Cotula cinerea, Asphodelus tenuifolius* and *Euphorbia guyoniana* 131 extracts, resins, oils and mother tinctures from 63 plants
Biological control	Actinomycètes *Pseudomonas* *Bacillus* Endophytic and other biocontrol fungi
nanomaterials	Eugenol oil nanoemulsions Chitosan nanoparticles
Approachs providing plant resistance	lipopolysaccharids N-acétylchitooligosaccharids – glycoproteins Jasmonic acid Bacterial isolates
Combination of different approachs	*Bacillus pumilus* + chitosan Botanical formulations + biocontrol agents

Combination of different approachs

Some researchers have tried to combine different biocontrol approachs to fight plants diseases. *Fusarium oxysporum* f. sp. *radicislycopersici* is a vascular fungus that attacks tomato. *Bacillus pumilus* alone or in combination with chitosan was evaluated for their capacity to induce plant resistance against this pathogenic fungus. Chitosan is a molecule extracted from chitin which is a natural fiber existing in shell of crustaceans and insects. The study was performed by light and transmission electron microscopy and gold cytochemistry. Ultrastructure analysis reported that in root tissues of plants treated only with bacteria (without chitosan), there was a limited development of the fungus and important changes in the host physiology compared to control. On the other hand, an increase in the cellular changes extent and magnitude was observed when chitosan was associated with bacteria. The same study showed that abnormal deposit of chitin-enriched (typical fungal cell reaction) was observed only when the plants were grown in the presence of both *Bacillus pumilus* and chitosan (Benhammou *et al.,* 1998). Akila *et al*. (2011) reported that combination of botanical formulations and biocontrol agents can have an important effect in the control of pathogenic fungi. Two botanical fungicides (Wanis 20 EC and Damet 50 EC) and two bacteria (*Pseudomonas fluorescens* 1, Pf1 and *Bacillus subtilis*, TRC 54) were tested indivdualy and in combination aginst *F. oxysporum* f. sp. *cubense* causing banana wilt. The results of his study, conducted in greenhouse and in field conditions, showed complete inhibition of mycelial growth of the pathogen. The effect of this combination was related to the production of peroxidase and polyphenol oxidase involved in plant defence.

Conclusion

Because of their devastating effect as plant pathogenic fungi, *Fusarium* species are a subject of many studies where researchers tried to find means to fight them. These studies are, in general, focusing on the use of natural products, plant extracts, bilogical control using potential agents like bacteria and fungi and approachs aiming to enhance plant resistance. Nanoparticles are other sophisticated materials studied in this sense.

References

Abd-Elsalam KA, Omar MR, Asran-Amal A, Mansour MT, Aly AA, 2014. Evaluation of a cotton germplasm collection against Fusarium wilt race 3 isolates from Egypt. *Trop. Plant Pathol*., **39**: 95-103.

Abd-Elsalam KA, Khokhlov AR, 2015. Eugenol oil nanoemulsion: antifungal activity against *Fusarium oxysporum* f. sp. *vasinfectum* and phytotoxicity on cottonseeds. *Appl. Nanosci.,* **5**: 255-265.

Abkhoo J, Panjehkeh N, 2017. Evaluation of antifungal activity of silver nanoparticles on *Fusarium oxysporum*. *Int. J. Infect.,* **4**: Article e41126.

Abro MA, Sun X, Li X, Jatoi GH and Guo LD, 2019. Biocontrol potential of fungal endophytes against *Fusarium oxysporum* f. sp. *cucumerinum* causing wilt in cucumber. *Plant Pathol. J.,* **35**: 598-608.

Aftab A, Yousaf Y, Javaid A, Riaz N, Younas A, Rashid M, Shamsher B, Arif A, 2019. Antifungal activity of vegetative methanolic extracts of *Nigella sativa* L. against *Fusarium oxysporum* and *Macrophomina phaseolina* and its phytochemical profiling by GC-MS analysis. *Int. J. Agric. Biol.,* **21**: 569-576.

Aichour SM, Gueehi A, Nicklin J, Deider D, Prevost H and Strange R, 2012. Isolation, identification and antimicrobial activity of pseudomonas isolated from the rhizosphere of potatoes growing in Algeria. *J. Plant Pathol.,* **94**: 89-98.

Akila R, Rajendran L, Harish S, Saveetha K, Raguchander T and Samiyappan R, 2011. Combined application of botanical formulations and biocontrol agents for the management of *Fusarium oxysporum* f. sp. *cubense* (Foc) causing Fusarium wilt in banana. *Biol. Control,* **57**: 175-183.

Akhtar R, Javaid A, 2018. Biological management of basal rot of onion by *Trichoderma harzianum* and *Withania somnifera. Planta Daninha,* **36**: Article e017170507.

Akhtar R, Javaid A, Qureshi MZ, 2020. Bioactive constituents of shoot extracts of *Sisymbrium irio* against *Fusarium oxysporum* f. sp. *cepae. Planta Daninha,* **38**: Article e020200961.

Asam S., Habler K. and Rychlik M, 2017. Chemical contaminations and residues in Food in Food, 2nd Edition, Dieter Schrenk & Alexader Cartus, UK, pp. 618.

Bacon CW, Yates IE, Hinton DM and Meredith F, 2001. Biological control of *Fusarium moniliforme* in maize. *Environ. Health Perspect.,* **109**: 325-332.

Badji B, Riba A, Mathieu F, Lebrihi A and Sabaou N, 2005. Antifungal activity of a saharan Actinomadura strain against various pathogenic and toxinogenic fungi. *J. Mycol. Méd.,* **15**: 211-219.

Bajwa R, Javaid A, Shah MBM, 2003a. Extent of shisham (*Dalbergia sissoo* Roxb.) decline in Sialkot, Gujranwala, Lahore and Sargodha districts. *Mycopath,* **1**: 1-6.

Bajwa R., Javaid A, Mirza JH, Akhtar N, 2003b. Chemical control of wilt in shisham (*Dalbergia sissoo* Roxb.). *Mycopath,* **1**: 111-113.

Bajwa R, Mukhtar I, Anjum T, 2004. *In vitro* biological control of *Fusarium solani* cause of wilt in *Dalbergia sissoo* Roxb. *Mycopath,* **2**: 11-14.

Bakkali F, Averbeck S, Averbeck D and Waomar M, 2008. Biological effects of essential oils : a

review. *Food Chem. Toxicol.,* **46**: 446-475.
Benhamou N, Kloepper JW and Tuzun S, 1998. Induction of resistance against Fusarium wilt of tomato by combination of chitosan with an endophytic bacterial strain: ultrastructure and cytochemistry of the host response. *Planta,* **204**: 153-168.
Bilska K, Stuper-Szablewska K, Kulik T, Busko M, Zaluski D, Jurczak S, Perkowski J, 2018. Changes in phenylpropanoid and trichothecene production by *Fusarium culmorum* and *F. graminearum* via exposure to flavonoids. *Toxins,* **10**: Article 110.
Bollina V, Kushalappa AC, Choo TM, Dion Y and Rioux S, 2011. Identification of metabolites related to mechanisms of resistance in barley against *Fusarium graminearum*, based on mass spectrometry. *Plant Mol. Biol.,* **77**: 355-370.
Bowers JH, Locke JC, 2000. Effect of botanical extracts on the population density of *Fusarium oxysporum* in soil and control of fusarium wilt in the greenhouse. *Plant Dis.,* **84**: 300-305.
Braga PC, Sasso MD, Culici M, Alfieri M, 2007. Eugenol and thymol, alone or in combination, induce morphological altera- tions in the envelope of *Candida albicans*. *Fitoterapia,* **78**: 396-400.
Broyde H, Dore T, 2013. Effect of agricultural practices on food contamination by mycotoxines from *Fusarium* and *Aspergillus*. *Greener J. Microbiol. Antimicrob.,* **2**: 182-194.
Bubici G, 2018. *Streptomyces* spp. as biocontrol agents against Fusarium species. *GAB Rev.,* **13**: 1-15.
Cantore PL, Shanmugaiah V, Iacobellis NS, 2009 Antibacterial activity of essential oil components and their potential use in seed disinfection, *J. Agric. Food Chem.,* **57**: 9454-9461.
Caravon JL, Tene N, Bonafe E, Alyarangues J, Hotier L, Armengaud C, Treilhou M, 2014. Thymol as an alternative to pesticides: persistence and effects of Apilife Var on the phototactic behavior of the honeybee Apis mellifera. *Environ. Sci. Pollut. Res. Int.,* **7**: 4934-4939.
Costa BH, Ventura AJ and Meira DD, 2016. Antifungal activity of plant extracts with potential to control plant pathogens in pineapple. *Asian Pac. J. Trop. Biomed.,* **1**: 26-31
Creelman RA, Mullet JE, 1997. Biosynthesis and action of jasmonates in plants. *Annu Rev Plant Physiol. Plant Mol. Biol.*, **48**: 355-381.
Cueto-Wong MA, Rivas-Morales C, Alanís-Guzmán G, Oranday-Cárdenas A, Amaya-Guerra CA, Núñez-González A, Samaniego-Gaxiola JA, Cano-Ríos P, 2010. Antifungal properties of essential oil of mexican oregano (*Lippia berlandieri*) against *Fusarium oxysporum* f. sp. *lycopersici*. *Rev. Mex. Micol.,* **31**: 29-35.
Daferera DJ, Ziogas BN, Polissiou MG, 2003. The effective- ness of plant essential oils on the growth of *Botrytis cinerea, Fusarium* spp. and *Clavibacter michiganensis subsp. michi-ganensis*. *Crop Prot.,* **22**: 39-44.
Davis RM, Colyer PPD, Rothrock CS and Kochman JK, 2006. Fusarium Wilt of Cotton: Population Diversity and Implications for Management. *Plant Dis.*, **90**: 692-703.
Deepa N, Nayaka SC, Shankar ACU, Kumar VK, Niranjanaa S, Prakash HS, Rghavendra MP, 2012. Detection and management of seed-borne toxigenic *Fusarium verticillioides* by plant alkaloids. *J. Mycol. Plant Pathol.*, **42**: 161-166.
El Hassni M, El Hadrami A, Daayf F, Cherif M, Ait Barka E, El Hadrami I, 2007. Biological control of bayoud disease in date palm: Selection of microorganisms inhibiting the causal agent and inducing defense reactions. *Environ. Exp. Bot.*, **59**: 224-234.
El Hassni M, Jaiti F, Dihazi A, Ait Barka S, Daayf F, El Hadrami I, 2004. Enhancement of defence responses against bayoud disease by treatment of date palm seedling with a hypoaggressive *Fusarium oxysporum* isolates. *J Phytopathol.*, **152**: 1-8.
El Modafar C, 2010. Mechanisms of date palm resistance to Bayoud disease: Current state of knowledge and research prospects. *Physiol. Mol. Plant Pathol.*, **74**: 287-294.
Essalmani H, Lahlou H, 2004. Induction, by Trichoderma harzianum, of resistance in lentil to *Fusarium oxysporum* f. sp. *lentis*. *Actes Inst. Agron. Vet*., **24**: 51-58.
Ferdosi MFH, Khan IH, Javaid A, Sattar T, Munir A, 2020. Identification of antimicrobial constituents in essential oil of *Paulownia fortunei* flowers. *Mycopath,* **18**: 53-57.
Ferdosi MFH, Khan IH, Javaid A, Sattar T, 2021. Antibacterial activity of essential oil of *Paulownia fortunei* (Seem.) Hemsl. flowers. *J. Plant.,* **3**: 27-32.
Galeotti F, Barile E, Curir P, Dolci M, Lanzotti V, 2008. Flavonoids from carnation (*Dianthus caryophyllus*) and their antifungal activity. *Phytochem. Lett.*, **1**: 44–48
Ghasemi G, Alirezalu A, Ghosta Y, Jarrahi A, Safavi SA, Abbas-Mohammadi M, Barba FJ, Munekata PES, 2020. Domínguez R5, lorenzo JM5. composition, antifungal, phytotoxic, and insecticidal activities of *thymus kotschyanus* essential oil. *Molecules*, **4** : 25(5).
Giesbrech M, McCarthy M, Elliott ML, Ong K.L, 2013. First report of *Fusarium oxysporum* f. sp. *palmarum* in Texas causing Fusarium wilt of *Washingtonia robusta*. *Plant Dis*., **97**:

Article 1511.
Gogoi R, Dureja PS, Pradeep K, 2009. Nanoformulations-A safer and effective option for agrochemicals. *Indian Farm*., **59**: 7-12.
Gopalakrishnan S, Pande S, Sharma M, Humayun P, Kiran BK, Sandeep D, 2011. Evaluation of actinomycete isolates obtained from herbal vermicompost for the biological control of Fusarium wilt of chickpea. *Crop Prot.*, **30**: 1070-1078.
Hammerschmidt R, Metraux JP, Van Loon LC, 2001. Inducing resistance: a summary of papers at the first international symposium on induced resistance to plant diseases. *Eur. J. Plant Pathol*., **107**: 1-6.
Hanson LE, Howell CR, 2004. Elicitors of plant defense responses from biocontrol strains of *Trichoderma viren*. *Phytopathology*, **94**: 171-176.
Hiremani NS, Dubey SC, 2019. Phylogenetic relationship among Indian population of *Fusarium oxysporum* f. sp. *lentis* infecting lentil and development of specific SCAR markers for detection. *Biotechnology*, **9**: Article 196.
Isidore SA, Kouabenan A, Kiyinlma C, Noël ZG, 2018. Étude phytochimique et activité antifongique d'extraits de quelques Euphorbiaceae médicinales utilisées chez les Baoulé du district de yamoussoukro (cote d'Ivoire). *Eur. Sci. J.*, **14**: 1857.
Jaiti F, Dihazi A, EL Hadrami A, El Hassni M, El Hadrami I, 2004. Effect of exogenous application of jasmonic acid on date palm defense reaction against *Fusarium oxysporum* f. sp. *albedinis*. *Phytopathol. Mediterr*., **43**: 325-31.
Javaid A, Bajwa R, Javaid A, 2005. Fusarium root and stem rot of *Erythrina suberosa* Roxb. in Pakistan. *Pak. J. Phytopathol.,* **17**: 105-107.
Javaid A, Afzal L, Bashir A, Shoaib A, 2014. *In vitro* screening of *Trichoderma* species against *Macrophomina phaseolina* and *Fusarium oxysporum* f. sp. *lycopersici*. *Pak. J. Phytopathol.,* **26**: 37-41.
Javaid A, Akhtar R, 2015. Antifungal activity of methanolic root extract of *Withania sommnifera* against *Fusarium oxysporum* f. sp. *cepae*. *Afr. J. Trad. Complement. Altern. Med.,* **12**: 22-27.
Javaid A, Latif U, Akhtar N, Ahmed D, Perveen S, 2018. Molecular characterization of *Fusarium moniliforme* and its management by methanolic extract of *Coronopus didymus. Pak. J. Bot.,* **50**: 2069-2075.
Javaid N, Shah MH, Khan IH, Javaid A, Waleed SM, 2020. Herbicidal activity of *Ageratum conyzoides* against parthenium. *Pak. J. Weed Sci. Res.,* **26**: 137-146.
Javed S, Mahmood Z, Khan KM, Sarker SD, Javaid A, Khan IH, Shoaib A, 2021. Lupeol acetate as a potent antifungal compound against opportunistic human and phytopathogenic mold *Macrophomina phaseolina*. *Sci. Rep.,* **11**: Article 8417.
Joyce KS, Silva JRA, Nascimento SB, Shirlley FM da Luz, Erisléia N Meireles, Cláudio N Alves, Alessandra R Ramos and JGS Maia, 2014. Antifungal activity and computacional study of constituents from *Piper divaricatum* essential oil against *Fusarium* infection in black pepper. *Molecules,* **19**: Article 1.
Kanwal Q, Hussain I, Siddiqui HL, Javaid A, 2010. Antifungal activity of flavonoids isolated from mango (*Mangifera indica* L.) leaves. *Nat. Prod.Res.,* **24**: 1907-1914.
Karlsson I, Friberg H, Kolseth AK, Steinberg C, Persson P, 2017. Agricultural factors affecting Fusarium communities in wheat kernels. *Int. J. Food Microbiol*., **252**: 53-60.
Ketabchi S and Shahrtach M, 2011. Effects of methyl jasmonate and cytokinin on biochemical responses of maize seedlings infected by *Fusarium moniliforme*. *Asian J. Exp. Biol. Sci*., **2**: 299-305.
Khan SN, Riaz T, Javaid A, 2010. Preceding crops affect the growth and mycorrhizal colonization of gladiolus (*Gladiolus grandiflorus* sect. Blandus) cv. Aarti under biotic stress of *Fusarium oxysporum* f. sp. *gladioli* (Massey) Snyd. & Hans. *Philipp. Agric. Sci.,* **93**: 135-141.
Khan IH, Javaid A, 2019. Antifungal, antibacterial and antioxidant components of ethyl acetate extract of quinoa stem. *Plant Prot.,* **3**: 125-130.
Khan IH, Javaid A, 2020. Anticancer, antimicrobial and antioxidant compounds of quinoa inflorescence. *Adv. Life Sci.,* **8**: 68-72.
Kheiri AA, Malihipour H, Saremi M, Nikkhah, 2017. Synthesis and characterization of chitosan nanoparticles and their effect on Fusarium head blight and oxidative activity in wheat. *Int. J. Biol. Macromol.,* **102**: 526-538.
Khurshid S, Shoaib A, Javaid A, 2014. *In vitro* toxicity evaluation of culture filtrates of *Fusarium oxysporum* f. sp. *lycopersici* on growth and physiology of tomato under chromium (VI) stress. *J. Anim. Plant Sci.,* **24**: 1241-1245.
Khurshid S, Shoaib A, Javaid A, 2016. Chromium toxicity to tomato (*Lycopersicum esculentum* Mill) susceptible to Fusarium wilt pathogen. *Curr. Sci.,* **110**: 399-403.
Khurshid S, Shoaib A, Javaid A, Akhtar F, Shafique M, Qaisar U, 2017. Management of Fusarium wilt of tomato by soil amendment with *Cenchrus pennisetiformis* under chromium stress. *Physiol. Mol. Plant Pathol.,* **97**: 58-68.
Khurshid S, Javaid A, Shoaib A, Javed S, Qaiser U,

2018. Antifungal activity of aerial parts of *Cenchrus pennisetiformis* against *Fusarium oxysporum* f. sp. *lycopersici*. *Planta Daninha,* **36**: Article e017166627.

Kobert M, Dita M, Martinuz A, Staver C, Berg G, 2017. Members of Gammaproteobacteria as indicator species of healthy banana plants on Fusarium wilt-infested fields in Central America. *Sci. Rep.*, **27**: 45318.

Kra KD, Diallo HA, Kouadio JY, 2009. Activités de *Chromolaena odorata* (L) King and Robins sur deux isolats de *Fusarium oxysporum* responsables du jaunissement mortel des feuilles de bananiers. *J. Appl. Biosci*., **24**: 1488-1496.

Laila S, 2020. Enhancement of secondary metabolites in Bacopa monnieri (L.) Pennell plants treated with copper-based nanoparticles *in vivo*. *IET Nanobiotechnol.*, **14**: 78-85.

Lepoivre P, Semal J, 1993. Les relations hôtes-parasites *In:* Traité de Pathologie Végétale, *Les Presses Agronomiques de Gembloux.*, pp. 249-302.

Li ZZ, Chen JF, Liu F, Liu AQ, Wang Q, Sun HY, Wen LX, 2007. Study of UV-shielding properties of novel porous hollow silica nanoparticle carriers for avermectin. *Pest Manage Sci.*, **63**: 241-246

Ling B, Zhang M, Kong C, Pang X, Liang G, 2003. Chemical composition of volatile oil from Chromolaena odorata and its effects on plant, fungi and insect growth. *Ying Yong Sheng Tai Xue Bao*, **14**: 744.

Lombard L, Van der Merwe NA, Groenwald JZ, Crous PW, 2015. Generic concepts in Nectriaceae. *Stud. Mycol.*, **80**: 189-245

Loreto ES, Mario DA, Santuro JM, Alves SH, Nogueira CW, Zeni G, 2011. *In vitro* antifungal evaluation and structure-activity relationship of diphenyl diselenide and synthetic analogues. *Mycoses*, **54**: 572-576.

Marei GK, Abdel Rasoul MA, Abdelgaleil SAM, 2012. Comparative antifungal activities and biochemical effects of monoterpenes on plant pathogenic fungi. *Pest. Biochem. Physiol.*, **103**: 56-61

Matan N, Nisoa M, Matanc N, Aewsiri T, 2014. Effect of cold atmospheric plasma on antifungal activities of clove oil and eugenol against molds on areca palm (*Areca catechu*) leaf sheath. *Int. Biodeterior Biodegrad.*, **86**: 196-201.

Mathesius U, 2018. Flavonoid functions in plants and their interactions with other organisms. *Plants*, **7**: Article 30.

Meghdas I, Hamze M, Dabboussi F, Baida N, Izard D, 2004. Taxonomie du genre *Pseudomonas*: Rétrospective et actualité. *Leban. Sci. J.*, **5**: 115-138.

Mekonnen M, Wariyo A, Hilu G, 2019. Antifungal activities of some essential oils against *Fusarium oxysporum* of rosemary and sage plants. *Adv. Crop Sci. Technol.*, **7**: Article 419.

Million CR, Vijeratne S, Cassone BJ, Lee S, Roof Mian MA, McHale LK and Dorrance AE, 2019. Hybrid genome assembly of a major quantitative disease resistance locus in soybean toward *Fusarium graminearum. Plant Genome.,* **12**: Article 180102.

Momma N, Momma M, Kobara Y, 2010. Biological desinfection using ethanol : Effect on *Fusarium oxysporum* f. sp. *lycopersici* and soil microorganisms. *J. Gen. Plant Pathol.*, **76**: 336-344.

Morcia C, Malnati M and Terzi V, 2012. *In vitro* antifungal activity of terpinen-4-ol, eugenol, carvone, 1,8-ciEONle (eucalyptol) and thymol against mycotoxigenic plant pathogens. *Food Addit. Contam. Part A*, **29**: 415-422.

Mukhtar I, Bajwa R, Ashraf A, Javaid A, Shah MBM, 2006. Complimentary effect of *Trichoderma harzianum* and some allelopathic plant extracts on *Fusarium solani. Int. J. Biol. Biotechnol.,* **3**: 77-80.

Naqvi SF, Javaid A, Qureshi MZ, 2019. Evaluation of antifungal potential of leaf extract of *Chenopodium murale* against *Fusarium oxysporum* f. sp. *lycopersici. Planta Daninha,* **37**: e019199050.

Nawaz U, Khan IH, Javaid A, Shad N, 2020. Response of *Fusarium oxysporum* f. sp. *cepae* to methanolic shoot extract of *Chenopodium murale*. *Mycopath,* **18**: 11-14.

Naz S, Javaid A, Ahmad N, Shoaib A, 2014. Antibacterial activity of essential oils of *Trachyspermum ammi* (L.) Sprague and *Ocimum basilicum* L. against *Acidovorax* sp. *Int. J. Biol. Biotechnol.,* **11**: 671-675.

Nelson PE, Toussoun TA, Cook RJ, 1994. *Fusarium*: diseases, biology and taxonomy. *Clin. Microbiol. Rev.,* **7**: 479-504.

Nesvorna M, Gabrielova L and Hubrt J, 2012. Suitability of a range of Fusarium species to sustain populations of three stored product mite species (Acari: Astigmata). *J. Stored Prod. Res.*, **48**: 37-45.

Noudogbessi JP, Kossou D, Sohounhloue CK, 2008. Composition chimique et proprietes physico-chimiques des huiles essentielles de *Pimenta racemosa* (Miller) et *de Chromolaena odorata* (L. Robinson) acclimatees au benin. *J. Soc. Ouest-Africaine Chimie*., **26**: 11-19.

Ntie-Kang F, Njume LE, Malange YI, Günther S, Sippl W, Yong JN, 2016. The chemistry and biological activities of natural products from northern african plant families: from taccaceae to Zygophyllaceae. *Nat. Prod. Bioprospect*., **6**: 63-96.

Nurnberger T, Lipka V, 2005. Non-host resistance in plants: new insights into an old phenomenon.

Mol. Plant Pathol., **6**: 335-345.

Ojha S, Chatterjee NC, 2012. Induction of resistance in tomato plants against *Fusarium oxysporum* f. sp. *lycopersici* mediated through salicylic acid and *Trichoderma harzianum*. *J. Plant Prot. Res.*, **52**: 221-225.

de Oliveira Pereira F, Mendes JM, de Oliveira Lima E, 2013. Investigation on mechanism of antifungal activity of eugenol against *Trichophyton rubrum*. *Med. Mycol.,* **51**: 507-513.

Omar NH, Mohd M, Mohamed-Nor NM, Zakaria L, 2018. Characterization and pathogenicity of Fusarium species associated with leaf spot of mango (*Mangifera indica* L.). *Mocrob. Pathog*., **114**: 362-368.

Reina M, Gonzalez-coloma C, Gutierrez R, Cabrera J, Henriquez J, Villarroe L, 1997. Bioactive saturated pyrrolizidine alkaloids from *Heliotropium floridum*. *Phytochemistry*, **46**: 845-853.

Reis A, Boitetux LS, 2007. Outbreak of *Fusarium oxysporum f. sp. lycopersici* race 3 in commercial fresh-market tomato fields in Rio de Janeiro State, Brazil. *Hort.Bras*., **25**: 451-454.

Riaz T, Khan SN, Javaid A, 2010. Management of Fusarium corm rot of gladiolus (Gladiolus grandiflorus sect. Blandus cv. Aarti) by using leaves of allelopathic plants. *Afr. J. Biotechnol.,* **9**: 4681-4686.

Reitz M, Rudolph K, Schroder I, Hoffmann-Hergarten S, Hallmann J, Sikora RA, 2000. Lipopolysaccharides of *Rhizobium etli* strain G12 act in potato roots as an inducing agent of systemic resistance to infection by the cyst nematode *Globodera pallida*. *Appl. Environ. Microbiol*., **66**: 3515-3518.

Rodriguez PAT, Arribato MA, Bautista BS, Cruz TA, Rivero D, 2012. Antifungal activity of *Acacia farnesiana* extracts on the *in vitro* growth of *Fusarium oxysporum f. sp. lycopersici. Rev. Sci. UDO Agric.*, **12**: 91-96.

Rosado-Álvarez C, Molinero-Ruiz L, Rodríguez-Arcos R, Basallote-Ureba MJ, 2014. Antifungal activity of asparagus extracts against phytopathogenic *Fusarium oxysporum*. *Sci. Hort*., **171**: 51-57.

Rosello CJ, Sempere FF, Sanz BI., Chiralt BMA, Santamarina SMP, 2015. Antifungal activity and potential use of essential oils against *Fusarium culmorum* and *Fusarium verticillioides*. *J. Essent. Oil Bear. Plants*, **18**: 359- 367.

Sadfi N, Cherif M, Hajlaoui MR, Boudabbous A, 2002. Biollogical control of the potato tubers dry rot caused by *Fusarium roseum* var. *sambucinum* undrer green-house, field and storage conditions using *Bicillus spp*. isolates. *J. Phytopathol*., **150**: 640-648

Sahi IY, Khalid AN, 2007. In vitro biological control of *Fusarium oxysporum* causing wilt in *Capsicum annuum*. *Mycopath*, **5**: 85-88.

Saleh AA, Sharafeddine AH, El-Komy MH, Ibrahimi YE, Hamad YK, Molan YY, 2017. *Fusarium* species associated with date palm in Saudi Arabia. *Eur. J. Plant Pathol*., **148**: 367-377.

Salhi N, Saghir MSA, Terzi V, Brahmi I, Gherairi N, Bissati S, 2017. Antifungal activity of aqueous extracts of some dominant Algerian medicinal plants. *Biomed Res. Int*., **75**: Article 6291.

Scherm B, Balmas V, Anfantino A, Aragono M, Valente MT, Desiderio F, Marcello A, Burgess LW, Rau D, 2019. Phanthavong S., Clonality, spatial structure, and pathogenic variation in *Fusarium fujikuroi* from rain-fed rice in southern Laos. *Plos One*, **14**: Article e0226556.

Sharf W, Javaid A, Shoaib A, Khan IH, 2021. Induction of resistance in chili against *Sclerotium rolfsii* by plant growth promoting rhizobacteria and *Anagallis arvensis*. *Egypt. J. Biol. Pest Control,* **31**: 16.

Sharma A, Rajendran S, Srivastava A, Sharma S, Kundu B, 2017. Antifungal activities of selected essential oils against *Fusarium oxysporum* f. sp. *lycopersici* 1322, with emphasis on *Syzygium aromaticum* essential oil. *J. Biosci. Bioeng*., **123**: 308-313.

Silva AM, Weidenborner M, Cavaleiro JAS, 1998. Growth control of different *Fusarium* species by selected flavones and flavonoid mixtures. *Mycol. Res*., **102**: 638-640.

Sindhu SS, Gupta SK, Dadarwal KR, 1999. Antagonistic effect of *Pseudomonas spp.* on pathogenic fungi and enhancement of growth of green gram (*Vigna radiata*). *Biol. Fert. Soil.*, **29**: 62-68.

Slinski SL, Zakharof F, Gordon TL, 2015. The effect of resin and monoterpenes on spore germination and growth in *Fusarium circinatum*. *Phytopathology*, **105**: Article 119-125.

Skadhauge B, Thomsen KK, Wettstein D, 1997. The role of the barley testa layer and its flavonoid content in resistance to fusarium infections. *Hereditas*, **126**: 147-160.

Soylu EM, Incekara R, 2017. Biofungicidal activities of plant essential oils against cucumber root and stem rot disease caused by *Fusarium oxysporum* f. sp. *radicis-cucumerinum*. *J. Plant Pathol*., **99**: 437-444.

Sreenivasa MY, Dass RS, Charith RAP, Nagendra PMN, Achar PN, Gotravalli JR, 2011. Assessment of the growth inhibiting effect of some plant essential oils on different *Fusarium* species isolated from sorghum and maize grains. *J. Plant Dis. Prot*., **118**: 208-213.

Sunil M, Hoskins C, 2017. Drug development:

Lessons from nature. *Biomed. Rep.*, **6**: 612-614.

Tahir A, Khan SN, Javaid A, Riaz M, 2018. Morphological and molecular characterization of *Fusarium thapsinum,* causing stalk tot of maize in Punjab, Pakistan. *Mycopath,* **16**: 57-64.

Tepe B, Daferera D, Sokmen A, Sokmen M, Polissiou M, 2005. Antimicrobial and antioxidant activities of the essen- tial oils and various extracts of *Salvia tomentosa* Miller (Lamiaceae). *Food Chem*., **90**: 333-340.

Thompson AH, Narayanin CD, Smith MF, Slabbert MM, 2011. A disease survey of Fusarium wilt and Alternaria blight on sweet potato in South Africa. *Crop Protection.*, **30:** 1409-1413.

Tosi L, Cappelli C, 2001. First Report of *Fusarium oxysporum* f. sp. *lentis* of lentil in Italy. *Plant Dis*., **85**: 562.

Um-e-Aiman, Nisar N, Tsuzuki T, Lowe A, Rossiter JT, Javaid A, Powell G, Waseem R, Al-Mijalli SH, Iqbal M, 2021. Chitin nanofibers trigger membrane bound defence signalling and induce elicitor activity in plants. *Int. J. Biol. Macromol.,* **178**: 253-262.

Wang SM, Liang Y, Shen T, Yang H, Shen BA, 2016. Biological characteristics of *Streptomyces albospinus* CT205 and its biocontrol potential against cucumber Fusarium wilt. *Biocontrol Sci. Technol.*, **26**: 95-63.

Woo KS, Kim KS, Lamsal K, Kim YJ, Kim SB, Jung M, Sim SJ, Kim HS, Chang SJ, Kim JK, Lee YS, 2009. An *in vitro* study of the antifungal effect of silver nanoparticles on oak wilt pathogen *Raffaelea* sp. *J. Microbiol. Biotechnol*., **19**: 760-764.

Yamaguchi T, Ito Y, Shibouya N, 2000. Oligosaccharide elicitors and their receptors for plant defense responses. *Trends Glycosci. Glycotechnol*., **12**: 113-120.

Yekkour A, Sabaou N, Zitouni A, Errakhi R, Mathieu F, Lebrihi A, 2012. Characterization and antagonistic properties of Streptomyces strains isolated from Saharan soils, and evaluation of their ability to control seedling blight of barley caused by *Fusarium culmorum*. *Lett. Appl. Microbiol*., **55**: 427-435.