Fusarium spp. Mycotoxin Production, Diseases and their Management: An Overview

Saba Shabeer¹, Riffat Tahira² and Atif Jamal³*

¹Department of Bioscience, COMSATS University, Islamabad, 44000, Pakistan; ²Social Sciences Research Institute (PARC), AARI, Jhang Road, Faisalabad, Pakistan; ³Crop Diseases Research Institute, National Agricultural Research Centre, Park Road, Islamabad, 45500, Pakistan.

Abstract | In total, more than 1.5 million fungal species exist in the world, amongst them pathogenic species can attack plants at different stages causing considerable damage amounting to millions of rupees. One of the plant pathogenic fungi is Fusarium spp. Fusarium species are very well-known soil-inhabiting fungi that cause many economically important diseases of crops. Many species are included in the Fusarium genus, which are not only pathogenic to plants but also cause different diseases in humans and livestock. Apart from diseases, one of the most dangerous characteristics of this fungus is the ability to produce dangerous secondary toxic metabolites, which are commonly known as mycotoxins. Some of the important toxins produced by different species of Fusarium are fumonisins and trichothecenes. Fusarium species are present around the world and have a very wide host range including many economically important species of crops and plants. Most of the plant diseases are caused by F. solani, F. oxysporum and F. graminearum. Fusarium species can infect grains in storage, but they are more prevalent in the field where they cause infection in crops and then may invade grains and cause infection in storage. Different methods including chemical, cultural, and biological control strategies are employed to control this fungus. In this review, mycotoxin production, characterization, identification, and different economically important diseases associated with Fusarium species as well as their control are discussed in detail.

Introduction

Fusarium is an important and well-known genus known as imperfect fungi. This genus consists of important plant pathogenic filamentous fungi (Suga and Hyakumachi, 2004). Over 20 species are included in the genus Fusarium, out of which 14 are plant pathogenic (Early, 2009). In these 14 species, Fusarium solani, Fusarium oxysporum and Fusarium chlamydosporum are the most common ones (De Hoog et al., 2000). Fusarium species are present around the world from tropical to temperate regions and even in harsh climates (Early, 2009). The species of the genus Fusarium also produce different mycotoxins and secondary metabolites. Zearalenone and giberellin are two important groups of metabolites that are used to enhance the growth of cattle and also as plant growth regulators respectively (Yu et al., 2004). Whereas, different mycotoxins like fumonisins and trichothecenes produced by Fusarium spp. can be fatal for animals and humans (Rheeder et al., 2002). If Fusarium contaminated food is consumed by animals...
Fusarium species impact on crops

and humans then it may cause mycotoxicosis in them (Kosmidis and Denning, 2017). *Fusarium* spp. may also act as important biodegrading agents and it can sustain in the soil for up to 16 years without any host as well as in dead and decaying plant material (Early, 2009). *Fusarium* species have a very broad host range. They cause economic losses in all cereal crops in North America and western Europe, cotton, wheat and barley in China, rice plants in Taiwan, Thailand and Japan, in all important crops in the tropics and worldwide in timber trees in the forest (Voigt, 2002).

All species of *Fusarium* can produce different secondary metabolites whose functions are still unknown or not properly understood. These secondary metabolites are different toxins that cause virulence during the development of diseases in plants. When mycotoxin contaminated grains are consumed by humans and livestock it may cause great health impact (Bakker et al., 2018). Symptoms produced by mycotoxins may vary depending upon the type as well as the concentration of mycotoxin (Bennett and Klich, 2003). The mycotoxins produced by different *Fusarium* species are trichothecenes, fumonisins and zearalenone (Table 1). Trichothecenes are the mycotoxins produced by 24 different species of *Fusarium*. These 24 species that produce trichothecenes are *Fusarium acuminatum*, *F. oxysporum*, *Fusarium avenaceum*, *F. poae*, *Fusarium camptoceras*, *F. proliferatum*, *F. chlamydosporum*, *F. sambucinum*, *F. compactum*, *F. scirpi*, *F. crookwellense*, *F. avenaceum*, *F. semitectum*, *F. culmorum*, *F. solani*, *F. equesiti*, *F. sporotrichioides*, *F. graminearum*, *F. subglutinans*, *F. moniliforme*, *F. tricinctum*, *F. nivale*, *F. tumidum*, *F. nygamai*, *F. venenatu* (Fuller, 2007; Mulé et al., 1997; Pitt and Hocking, 1997; Sweeney and Dobson, 1998). Zearalenone is the mycotoxins of *Fusarium graminearum* and some *Fusarium sambucinum* related species but they are not associated with the disease on wheat (Munkvold, 2017). Zearalenone is a beneficial mycotoxin as it is being used to increase the growth of cattle (Yu et al., 2004). Fumonisins mycotoxins are produced by the *F. verticilloides* (Desjardins and Plattner, 2000) and some other species of *Fusarium* like *Fusarium moniliforme*, *F. proliferatum* (Keller and Sullivan, 1996), *Fusarium napiforme* (Nelson et al., 1992) and *Fusarium nygamai* (Ihie et al., 1991). They are related to ear rot in corn, but they are not needed for disease-causing in corn (Desjardins and Plattner, 2000). Their adverse effects on the health of livestock as well as humans have been reported. They are very toxicogenic for kidney and liver as well as they are also carcinogenic in nature (Stockmann-Juvala and Savolainen, 2008). All the mycotoxins that are produced by different species of *Fusarium* and their effects are summarized in Table 1.

Control of mycotoxins produced by different *Fusarium* species

Mycotoxins produced by different fungal species can be detoxified by using chemicals, but it is not a commonly used method as crops subjected to these chemical treatments may become unsuitable for human consumption. However, different chemical treatments involved for the detoxification of mycotoxins are ammoniation, treatments with different acids, bases, oxidizing (e.g. ozone) or reducing (e.g. sodium bisulfite) agents and enzymatic degradation (Munkvold et al., 2019).

A well-studied method of mycotoxin management through chemicals is the treatment of contaminated products with ammonia or ammonium hydroxide. In a study, the treatment of contaminated products with 2% ammonia caused reduction in fumonisins up to 79% (Charmley and Prelusky, 1994). Treatments with calcium or sodium hydroxide have shown remarkable detoxification in feeds contaminated by aflatoxins, T-2, zearalenone and diacetoxyscirpenol from 45% to 99% depending upon the nature of the toxin as well as feed moisture level (Charmley and Prelusky, 1994; Karlovsky et al., 2016). Sodium bisulfite treatments were proved to be effective against deoxynivalenol in only animal feed corn as well as treatments with ozone and chlorine gas were only effective in detoxification of different mycotoxins in corn but not wheat (Young, 1986; Young et al., 1986). Formaldehyde and ammonium hydroxide were proved to be effective in decontaminating zearalenone affecting corn and corn grits, but the products treated with formaldehyde are unstable for human consumption (Charmley and Prelusky, 1994).

For the inactivation of mycotoxins through enzymatic treatments different products are commercially available which includes Mycofix, FUMzyme, Biomin BBSH 797, and Biomin MTV. Only a few enzymes have been discovered for the detoxification of fumonisins which includes esterases obtained from a yeast called *Spinifera exophiala* and amino transferase obtained from a bacterium *Sphingomonas* sp. Whereas, for the detoxification of different trichothecenes, UDP-glycosyltransferase was proved to be effective...
**Table 1:** List of mycotoxins produced by Fusarium spp. along with compounds of mycotoxins, mycotoxins producing species and their effect on humans and animals.

| S. no | Name of mycotoxin | Compound of mycotoxin | Mycotoxin producing spp. | Effect of mycotoxin | Reference |
|-------|-------------------|-----------------------|--------------------------|---------------------|-----------|
| 01.   | Trichothecenes    | Diacetoxyscirpenol     | *F. acuminatum*, *F. oxysporum*, *F. poae*, *F. campeosporum*, *F. proliferatum*, *F. oholmydiosporum*, *F. sambucinum*, *F. compactum*, *F. scirpi*, *F. crookwellense*, *F. semitectum*, *F. culmorum*, *F. solani*, *F. equiseti*, *F. sporotrichioides*, *F. graminearum*, *F. subglutinans*, *F. moniliforme*, *F. tricinctum*, *F. nivale*, *F. tupidum*, *F. nygamai*, *F. venenati* | Chronic and fatal toxicosis in human and animals such as Alimentary toxic Aleukia, Akakabi-byo (red mold disease) and Swine feed refusal | (Bullerman, 2007; Desjardins and Plattner, 2000; Mulè et al., 1997; Pitt and Hocking, 1997) |
| 02.   | Fumonisins        | Fumonisins B1          | *F. verticillioides*, *F. proliferatum*, *F. napiforme*, *F. dlamiini* and *F. nygamai* | Leukoencephalomalacia in horses, esophageal cancer and birth defects in humans | (Desjardins, 2006; Marin et al., 2013) |
|       |                   | Fumonisins B2          |                          |                     |           |
|       |                   | Fumonisins B3          |                          |                     |           |
| 03.   | Zearalenone        | -                     | *F. graminearum*, *F. culmorum*, *F. cerealis*, *F. equiseti*, *F. verticillioides* and *F. incarnatum* | Estrogenic syndromes in swine and used to increase the growth of cattle | (Desjardins, 2006; Marin et al., 2013; Pusateri and Kenison, 1993) |
| 04.   | Beavercin and Enniatins | -                 | *F. avenaceum*, *F. tricinctum*, *F. sporotrichioides*, *F. langethiae*, *F. sambucinum*, *F. verticilliode*, *F. sporotrichioides*, *F. proliferatum* and *F. subglutinans* | No effects | (Desjardins, 2006; Logrieco et al., 1998; Thrane, 2001) |
| 05.   | Butenolide         | -                     | *F. graminearum*         | Fescue foot in cattle and toxicity in mice | (Desjardins, 2006) |
| 06.   | Equisetin          | -                     | *F. semitectum* and *F. equiseti* | Toxic to mice, effect Human immunodeficiency virus and gram-positive bacteria | (Desjardins, 2006) |
| 07.   | Fusarins           | -                     | *F. verticillioides* and *F. graminearum* | Cause mutation | (Desjardins, 2006) |
| 08.   | Fusaproliferin     | -                     | *F. proliferatum* and *F. subglutinans* | Cause toxicity in Artemia Salina, L,6,10 IARC/LCL 171 human B lymphocytes and SF-9 insect cells as well as it has pathogenic effects on embryos of chicken | (Marin et al., 2013) |
| 09.   | Moniliformin       | -                     | *F. avenaceum*, *F. tricinctum*, *F. proliferatum*, *F. subglutinans*, and *F. verticillioides* | Cause interruption of gluconeogenesis and inhibit glutathione peroxidase and reductase | (Chen et al., 1990; Pirrung et al., 1996) |

while for the degradation of zearalenone different enzymes including laccases were reported to be effective (Karlovsky et al., 2016; Loi et al., 2017).

Biological detoxification of mycotoxins includes the use of different microorganisms or the use of different enzymes obtained from microorganisms. In some cases, there are reports of degraded products that are still toxic but, in some cases, there is the complete degradation of mycotoxins using mycotoxin-detoxifying microorganisms. Reduction in the level of deoxynivalenol up to 54%–56% has been seen in the feed when it is incubated with intestinal microflora of chickens (Charmley and Prelusky, 1994). For the detoxification of each of the common mycotoxins, at least one specific microorganism has been discovered (Zhu et al., 2016). Many microorganisms identified as mycotoxin degrading agents are bacteria especially Bacillus species.
The life cycle of Fusarium spp. 
Fusarium spp. follow both asexual and sexual life cycles. During both sexual and asexual stages, mycelial structures that are haploid are being established. Few species of Fusarium produce sexual (meiotic) spores viz. ascospores and three types of asexual (mitotic) spores viz. microconidia, macroconidia and chlamydospores that are produced from conidiophores, from sporodochium and within or on hyphae, respectively. Both stages produce spores that are airborne in nature and hence may cause infection and mycotoxin contamination in plants (Dweba et al., 2017). The generalized life cycle of Fusarium spp. is depicted in Figure 1. Not all species of Fusarium produce all kinds of spores and the sexual cycle of only less than 20% of Fusarium spp. is known (Ma et al., 2013).

Sexual state of Fusarium spp.
Teleomorph, which is the sexual state, is known of few Fusarium species. All sexual states of known Fusarium species are part of Ascomycota but included in different genera viz. Genus Gibberella and Genus Nectria etc. The teleomorphic species of Fusarium can be both heterothallic and homothallic. During meiosis, the chromosomes of few of these species was seen under light microscope but due to the small chromosome size of Fusarium species, the accurate number of chromosomes or karyotyping is not determined therefore, for this purpose pulsed field gel electrophoresis (PFGE) has been used (Suga and Hyakumachi, 2004). All the known perfect states of Fusarium species are given in Table 2.

Morphological and microscopic characteristic of Fusarium spp.
Fusarium spp. can grow on many media. When different Fusarium spp. are grown on potato dextrose agar, they may show white, lavender, pink, salmon, or gray-colored velvety to fuzzy cottony growth. Hyphae of Fusarium species is hyaline and septate, and it varies from 3 to 8μm in diameter. The species of Fusarium produce both macro as well as microconidia. Macroconidia produced by different Fusarium species are hyaline, multicellular, septate, and sickle-shaped which may appear in form of clusters while the microconidia are hyaline, unicellular, and ovoid to straight or slightly curved in shape. Sometimes chlamydooconidium are also produced by Fusarium species which may present as a single spore or in the shape of clusters or chains (Bullerman, 2003; Nucci and Anaissie, 2009).

Molecular identification of Fusarium spp.
Different molecular techniques which include Random Amplified Polymorphic DNA (RAPD) analysis, specific diagnostic PCR primers and DNA sequencing are being used to identify Fusarium species. The polymerase chain reaction (PCR) is considered

Table 2: Asexual state of Fusarium species with their known sexual state.

| S. No | Asexual state of Fusarium species (Anamorph) | Sexual/Perfect state of Fusarium species (Teleomorph) | Reference |
|-------|---------------------------------------------|-------------------------------------------------|----------|
| 01.   | Fusarium graminearum                        | Gibberellazae                                   | Khan et al., 2020 |
| 02.   | Fusarium moniliforme                        | Gibberellafujikuroi                             | Chang and Sun, 1975 |
| 03.   | Fusarium solani                             | Nectriahaematococca                             | Windels, 1991 |
| 04.   | Fusarium roseum var. avenaceum              | Gibberellaavenacea                              | Cook, 1967 |
| 05.   | Fusarium tumidum                            | Gibberellatumida                                | Broadhurst and Johnston, 1994 |
| 06.   | Fusarium sacchari                           | Gibberellasacchari                              | Leslie et al., 2005 |
| 07.   | Fusarium sambucinum                         | Gibberellapulicaris                              | O’Donnell, 1992 |
| 08.   | Fusarium verticillioides                    | Gibberella moniliformis                         | Jurgenson et al., 2002 |
| 09.   | Fusarium acuminatum                         | Gibberella acuminata                            | Elmer, 1996 |
| 10.   | Fusarium Lateritium                         | Gibberellabaccata                               | Afamide et al., 1976 |
| 11.   | Fusarium cincinatum,                        | Gibberellacincinata                             | Gordon et al., 2006 |
| 12.   | Fusarium pseudograminearum                  | Gibberellacononicoila                           | Aoki and O’Donnell, 1999 |
| 13.   | Fusarium heterosporum                       | Gibberellagerardoni                            | Sheraliev and Bukharov, 2001 |
| 14.   | Fusarium udum                               | Gibberella indica                               | Rai and Upadhyay, 1982 |
| 15.   | Fusarium gibbosum                           | Gibberellaintricans                             | Dutkiewicz et al., 2016 |
| 16.   | Fusarium proliferatum                       | Gibberella intermedia                           | Salvalaggio and Ridao, 2013 |
| 17.   | Fusarium xylarioides                        | Gibberellaxylarioides                           | Geiser et al., 2005 |
as the most reliable and rapid technique for the identification of different Fusarium species (Kachuei et al., 2015). Different primer sets have been designed for the identification of Fusarium species (Table 3).

Pathogenicity factors of Fusarium spp.

Fusarium spp. uses different cellular signaling pathways and different toxins or enzymes which may include MAPKs, Ras proteins, G-proteins, Velvet complex, cAMP pathways and cell wall degrading enzymes to enter their hosts and cause infection. These pathogenicity factors maybe generally produced by different species of Fusarium or they may be host-specific (Poppenberger et al., 2003).

| S. no | Primers | Fusarium spp. | Amplification (size bp) | Sequence | Reference |
|-------|---------|---------------|-------------------------|----------|-----------|
| 01.   | ITS 1 and ITS4 | Universal fungal primers | 550-570 bp | ITS1(5’TCC GTA GGT GAA CCT GCG G 3’) ITS4 (5’TCC TCC GCT TAT TGA TAT GC 3’) | (Abd-Elsalam et al., 2003; Ferrer et al., 2001) |
| 02.   | ITS-Fu-f & ITS-Fu-r | F. oxysporum f. sp. Vainfectum, F. oxysporum, F. moniliforme, F. solani | 398 bp | ITS-Fu-f(5’-CAACTCCCAAACCCCTGTGA-3’) ITS-Fu-r(5’-GCGACGATTACCAGTAACGA-3’) | (Abd-Elsalam et al., 2003) |
| 03.   | ITS5 & as7 | F. proliferatum, F. verticilloides, F. subglutinans, F. nygamai, F. oxysporum, F. compactum, F. sporothichoides, F. tricinctum, F. graminearum,F. pae, F. camptoceras, F. culmorum, F. pseudozymamai, F. avenaceum, F. thapsinum, F. acuminatum, F. habina, F. blamysdoroporum, F. diamini, F. heterosporum, F. cf. langsetheia, F. pseudograminearum and F. xylarioides | 930 bp | ITS5(5’GGAGTAAAAAGTCGTAACCGG3’) as 7 (5’CTTCCCCATTCAACAATTTCAC3’) | (Kachuei et al., 2015) |
| 04.   | Fg16F & Fg16R | Fusarium graminearum | 420-520 bp | Fg16F(CTCCCGGATATGGTTGCGTAA) Fg16R(GGTAGGTATGCCGACATGGCAA) | (Nicholson et al., 1998) |
| 05.   | OPT18F & OPT18R | F. culmorum | 470 bp | OPT18F (F-GAT GCC AGA CCA AGA CGA R-AG) OPT18R (GAT GCC AGA CGC ACT AAG ATG) | (Schilling et al., 1996) |
| 06.   | FAC-F & FAC-R | F. acuminatum | 600 bp | FAC-F (GGG ATA TCG GGC CTC A) FAC-R (GGG ATA TCG GCA AGA TCG) | (Williams et al., 2002) |
| 07.   | FEF & FER | F. equiseti | 400 bp | FEF (CAT ACC TAT ACG TTG CCT CG) FER (TTA CCA GTA ACG AGG TGT ATG) | (Mishra et al., 2003) |
| 08.   | Fp82F & Fp82R | F. pae | 220 bp | Fp 82F(CAAGCAAACAGGCTCTTCC) Fp 82R(TGTTCGACACCGCTTCC) | (Parry and Nicholson, 1996) |
| 09.   | SUBF & SUBR | F. subglutinans | 630 bp | SUBF(CAGTATGGACGTTGTTATATATC) SUBR(CAGTATGGACGTTGTTATATATC) | (Mulè et al., 2004) |
| 10.   | VERF & VERR | F. proliferatum | 420 bp | VERF(TGTCAAGTAACTCGAAGTGGTTG) VERR (CTTCCCCGATGTGTTTCTCC) | (Mulè et al., 2004) |

Diseases caused by Fusarium spp.

Species of Fusarium cause many diseases like root rots, seedling blight (Bakker et al., 2016), vascular wilts (Michielse and Rep, 2009), infection in reproductive tissues as well as in developing seeds (Kazan et al., 2012) and diseases in storage (Gachango et al., 2012). The Fusarium species have a wide host range. They can cause diseases in different cereal crops like maize, rice, wheat, barley, rye, oat and malt, etc. as well as in other vegetables and fruit crops like melons, pepper, potato, tomatoes and banana, etc. (Early, 2009). Most of the plant diseases are caused by Fusarium solani (50%) and by Fusarium oxysporum (20%) (Kosmidis and Denning, 2017). A comprehensive table has been

---

**Table 3: Molecular identification of Fusarium spp. using specific primer sets.**

June 2021 | Volume 34 | Issue 2 | Page 282
Fusarium species impact on crops

Fusarium species impact on crops

June 2021 | Volume 34 | Issue 2 | Page 283

made which shows all the diseases caused by Fusarium spp. in different plants (Table 4).

Disease symptoms
Fusarium spp. produces different types of symptoms on hosts. Some of the common symptoms produced by this fungus are described below.

Vascular wilt diseases
Wilt diseases are mostly caused by different species of Fusarium. Mostly all wilts show common symptoms like the infected parts of the plant lose their turgidity, their color changes to light green or yellowish green then to brown and they wilt and finally die. Wilting is due to the blockage in xylem tissue of plants by the spores, mycelium, or polysaccharides of fungus which results in the less flow of water in tissues of plants. The fungus also produces different mycotoxins like fusaric acid and lycomarasmin in vessels that flow from vessels to the leaves. In leaves, they affect the process of photosynthesis by reducing the production of chlorophyll (Voigt, 2002).

Rot diseases
Rots may affect the roots, foot, or stem of plants. Rots maybe caused by one or more than one pathogen (Waller and Brayford, 1990). The plant parts which are rotted may seem like water soaked and the color of the infected area turn brownish and finally black. Plant stops growing and roots, as well as stems, die due to rottting (Voigt, 2002). In the case of cereals, the rottting of the stalk happens which results in the

Table 4: List of diseases caused by Fusarium spp. on different hosts.

| S. no | Pathogen spp. | Disease caused | Host | Reference |
|------|---------------|----------------|------|-----------|
| 01.  | Fusarium sacchari | Sugarcane wilt | Sugarcane | (Viswanathan et al., 2011) |
| 02.  | Fusarium moniliforme | Pokkah Boeng | Sugarcane | (Vishwakarma et al., 2013) |
| 03.  | Fusarium fujikuroi | Bakane | Rice | (Wulff et al., 2010) |
| 04.  | Fusarium decemcellulare | Green point gall | Cacao | (Hansen, 1966) |
| 05.  | Fusarium manginifera | Flowering malformation | Mango | (Marasas et al., 2006) |
| 06.  | Fusarium oxysporum f. sp. elaeidis | Fusarium wilt | Oil palm | (Flood, 2006) |
| 07.  | Fusarium oxysporum f. sp. Lycoptersici | Fusarium wilt | Tomato | (Walker, 1971) |
| 08.  | Fusarium oxysporum f. sp. Cukhen | Panama disease | Abaca | (Voigt, 2002) |
| 09.  | Fusarium pallidoroseum | Crown rot | Banana | (Krauss and Johanson, 2000) |
| 10.  | Fusarium graminearum | Fusarium head blight | Wheat, Corn, Barley | (McMullen et al., 1997) |
| 11.  | Fusarium solani | Papaya internal fruit rot | Papaya | (Alvarez and Nishijima, 1987) |
|      | Root rot | Cassava | (Dandyradhyay et al., 2006) |
|      | Canker | Passion fruit | (Ploetz, 2003) |
|      | Slow decline | Pepper | (Oliveira and Pereira, 1983) |
| 12.  | Fusarium oxysporum f. sp. Ciceris | Fusarium Wilt | Chickpea | (Knights, 2004) |
| 13.  | Fusarium moniliforme | Fusarium ear rot of corn | Corn | (Davis et al., 1989) |
| 14.  | Fusarium decemcellulare | Dieback of mango | Mango | (Qi et al., 2013) |
| 15.  | Fusarium oxysporum f. sp. Angsanae | Wilt | Angsana | (Crowhurst et al., 1995) |
| 16.  | Fusarium xylarioides | Wilt | Coffee | (Rutherford, 2006) |
| 17.  | Fusarium oxysporum f. sp. Vasinfectum | Fusarium wilt | Cotton | (Holliday, 1980) |
| 18.  | Fusarium oxysporum f. sp. Passiflora | Fusarium wilt | Passion fruit | (Ploetz, 2003) |
| 19.  | Fusarium circinatum | Pitch canker | Pine | (Gordon, 2006) |
| 20.  | Fusarium guttiforme | Fusariosis | Pineapple | (Ventura, 1994) |
| 21.  | Fusarium oxysporum f. sp. Rosellae | Fusarium wilt | Rosella | (Ooi and Salleh, 1999) |
| 22.  | Fusarium oxysporum f. sp. Vanilla | Stem and root rot | Vanilla | (Ben-Yephet et al., 2003; Liew et al, 2004) |
| 23.  | Fusarium solani f. sp. Eumartii | Foot rot | Tomato, Potato, eggplant & pepper | (Romberg and Davis, 2007) |
| 24.  | Fusarium oxysporum f. sp. phaseoli | Fusarium wilt or yellows | Beans | (de Vega-Bartol et al., 2011) |
The blight of seedlings mostly caused on corn and small grains as dark brown lesions that resemble brown rot and blight in both at pre- and post-emergence stage. The seedlings may not develop properly, chlorosis will occur which finally results in the death of seedling (Voigt, 2002).

Head blight or Scab diseases
Scab appears on spikelet as water-soaked lesions which later decolorize. During warm and humid conditions, the head fully gets infected through mycelia and conidia and the kernels get dry and shriveled. Mycelium of fungus overgrows and appears as white, pink, or brown growth on infected kernels (Voigt, 2002).

Dry rot diseases
Dry rot may infect bulbs, corms, and tubers on both pre- and post-harvest stages. The most common hosts of dry rot diseases are onion, lily, gladiolus, and potatoes. The injuries caused during harvesting are the main way of pathogen invasion. Brown colored small lesions will form on tubers which increase in size and later wrinkles will form. Tubers become hard and mummified (Voigt, 2002).

Management of diseases caused by Fusarium species
Cultural control practices help to reduce the primary inoculum which is responsible for the development of secondary infection. Diseases in plants caused by Fusarium spp. can be controlled by achieving low plant density, using proper phosphate, potassium, and nitrogen fertilizers, and using resistant varieties of plants. Rotation of crops, tillage and proper seedbed preparation can also reduce the primary inoculum present in crop residues. The first-ever method used to control the plant diseases was crop rotation (Sumner, 1994). But it is not useful in the case of Fusarium spp. which are not specialized because they have a wide host range (Waller and Brayford, 1990). Losses caused by Fusarium spp. can be decreased by crop rotation with resistant or non-host crops, attaining suitable soil drainage and by using healthy and treated stock (Agrios, 1997). Disease development can also be controlled by changing the date of sowing because it is affiliated with the epidemic development. Crops like chickpea have been sown in southern Spain in early winters instead of early springs which helped in slowing the epidemics of Fusarium wilt which resulted in less disease development (Navas-Cortés et al, 1998). Sowing the crops in early winter instead of early spring resulted in more soil moisture and less temperature which are not favorable for Fusarium wilt thus it affects the disease development (Voigt, 2002). Primary inoculum of Fusarium can also be decreased by flooding fields for a large period or dry fallowing because it results in a low oxygen level which is not favorable for pathogen development (Manners, 1993). Infection of Fusarium in seeds can be controlled by decreasing the temperature and moisture in storage for several months because it decreases the activity of Fusarium graminearum in grains (Gilbert et al, 1997). By achieving the temperature below 10°C, growth and mycotoxin production can be lowered in F.graminearum, F. moniliforme and F. proliferatum (Ryu and Bullerman, 1999; Ryu et al., 1999). Food preservatives like sorbic acid, acetic acid, formic acid and propionic acid, etc. can be used to decrease the mycelial growth and production of spores and mycotoxins by different Fusarium spp. like F. proliferatum (Marín et al., 1999) and F. oxysporum.
**Fusarium species impact on crops**

Chemical control

The use of chemical control strategies such as fungicide seed treatment and the application of fungicides on crops along with cultural control strategies can be effective to control diseases. Studies have been done to check the effect of treatments on seeds which helped in better understanding of different chemical treatment effects on viability, germination, emergence and vigor of seeds as well as the weight of roots (Gilbert and Tekauz, 1995; Gilbert et al., 1997). Rots caused by *Fusarium* spp. can be controlled by applying benomyl sprays on plants or by treating propagative plant materials with benomyl. Benzimidazoles and Benomyl works very well against the infections caused by *Fusarium* species. Benzimidazoles are very effective against the *F. avenaceum*, *F. culmorum*, *F. equiseti* and *F. solani*, but it is not effective against the *F. sambucinum* which causes tubers in potatoes because it is highly resistant to benzimidazole and its derivatives (Kawchuk et al., 1994). While prochloraz and tebuconazole are effective against *F. culmorum* and *F. poae* which are the causal agents of ear blight on wheat (Doohan et al., 1999). In storage conditions, diseases on crops can be managed by applying fungicides at the post-harvest stage. For example, a pathogen causing dry rot of potato tubers only enters its host through physical injuries. After it enters its host, it develops inside the host and causes infection but its development inside the host can be controlled by treating the potatoes with thiabendazole at the post-harvest stage (Sécor and Gudmestad, 1999). When plants are treated with benzimidazole then on the surface of plants they convert into methyl benzimidazole carbamate (MBC, carbendaziam) which acts as a systemic fungicide and are fungistatic in nature (Manners, 1993). Organomercury fungicides act both as eradicants and protectants and they are used to control *Fusarium* diseases in cereal grains (Häni, 1981; Manners, 1993). In China, bakanae disease of rice has been successfully managed by treating seeds with formalin and organic mercury (Cook, 1967). But formalin and organic mercury-based fungicides have toxic effects on plants. Another safe method to control *Fusarium* diseases is by treating the soil with fumigants like methyl bromide before the sowing of crops. This fumigant enters in the pores of soil, spread thoroughly and has no toxic effect (Ben-Yephet et al., 1994). Soil is treated with both volatile fumigant methyl bromide and insecticide chloropicrin together. Metalaxyl, diazoben, pentachloronitrobenzene (PCNB), ethazol, captan and chloroneb are the most common organic fungicides which are used to treat the soil. They are more effective, safe but are expensive than sulfur-based and copper-based fungicides. Captan which act as a protectant, reacts with sulphydryl groups and stops the activity of enzyme which contains thiol (Manners, 1993). Many *Fusarium* spp. develop resistance against fungicides and fungicide may not remain effective against those isolates which will ultimately increase the diseases caused by *Fusarium* (Sécor and Gudmestad, 1999). Therefore, along with chemical control we must use other control measures like use of proper cultivation techniques, proper treatment of seeds and usage of clean and healthy seed and propagating stock etc. (Voigt, 2002).

Biological control

Fusarium against Fusarium: Some species of pathogens contain virulent, avirulent or hypovirulent strains. These two avirulent or hypovirulent strains can be used against the virulent strain. These virulent or hypovirulent strains can protect the crop against its virulent strain (Sneh, 1998). The avirulent strains increase the resistance of host plants against its pathogen by competing with the virulent strains. Some strains of *Fusarium* also produce anti-fungal compounds like alpha-pyrones produced by *F. semitectum* which play an important role in the protection of plants (Evidente et al., 1999). For example, Wilts caused by *Fusarium oxysporum* in different crops was managed by using avirulent strains of the same fungus (Fravel and Engelkes, 1994).

Fungi against Fusarium: Mycorrhizal association with the roots have successfully managed the disease caused by *F. oxysporum* in Doubla fire seedlings and *F. solani* in soybean same as in the case of ectomycorrhizal and endomycorrhizal associations which increases the plant health resulted in less development of pathogens like *F. oxysporum*, *F. solani*, *F. culmorum* and *F. graminearum* in their respective hosts (Schönbeck et al., 1994). The *Trichoderma* is also one of the successful bio-control agents of *Fusarium*. It affects the growth of *Fusarium* by causing parasitism (Ogawa et al., 2000). *Trichoderma* spp. effects and degrade the chitin which is the main constituent of the cell wall of fungus (Manocha and Govindsamy, 1998). *Trichoderma viridae* successfully controlled the diseases caused by *F. moniliforme* as well as reduced...
its mycotoxin production by 85% (Yates et al., 1999). *F. oxysporum f. sp. lycopersici* which causes wilt was controlled in tomatoes by 30% using *Penicillium purpurogenum* as a bio-control agent (Larena and Melgarejo, 1996).

**Bacteria against Fusarium:** Rots and damping-off diseases caused by *Fusarium* have been successfully managed by using *Bacillus cereus* which is a soil-borne bacteria whereas, *Pseudomonads* are being successfully used against *F. oxysporum* because they produced antibiotics such as N-butylbenzene sulfonamide which inhibits the activity of *F. oxysporum* (Kim et al., 2000). *Pseudomonads* especially *P. fluorescens* and *P. putida* are abundantly present in soil rhizosphere. They make soil suppressive against the wilts causing *Fusarium* by producing siderophores (Alabouvette et al., 1998). *P. putida* promotes the production of phenolic compounds in cucumber which are antifungal in nature. This helps in the increase of resistance against the pathogen (Ongena et al., 2000). The health of potato plants has been increased by the induction of *Pseudomonas* which promotes siderophores that are hydroxamate type which resulted in the production of hydrocyanic acid and indole acetic acid (Gupta et al., 1999). Salicylic acid is an important signaling molecule in plant defense systems which plays an important role in the induction of resistant mechanisms in plants (Mauch-Mani and Métraux, 1998). If the activation of salicylic acid is affected, then it increases the susceptibility level of the host against its pathogens (Delaney et al., 1994). Rhizobacteria increase the plant health by inducing ISR in plants through the production of compounds like indole-3-acetic acid and cytokinin along with the reduction of ethylene (Buchenauer, 1998).

**Mycoviruses against Fusarium:** Studies have shown that mycoviruses cause a reduction in the virulence of fungi known as hypovirulence therefore they can be used as bio-control agents (Nuss, 2005). Different mycoviruses have been discovered from different *Fusarium* species. *Fusarium graminearum* virus 1 (FgV1), *Fusarium graminearum* virus DK21 (FgV-DK21), *Fusarium graminearum* virus 2 (FgV2), *Fusarium graminearum* virus China 9 (FgV-ch9), *Fusarium graminearum* hypovirus 1 (FgHV1), *Fusarium graminearum* hypovirus 2 (FgHV2) and *Fusarium graminearum* mycotoymovirus 1 (FgMTV1) have been discovered from different isolates of *Fusarium graminearum* and they affect them by causing hypovirulence, less mycotoxin production, altered growth and irregular morphology (Chu et al., 2002, 2004; Darissa et al., 2012; Li et al., 2016, 2015; Wang et al., 2013; Yu et al., 2011) same as in case of *Fusarium boothi* large flexivirus 1 (FbLFV1), *Fusarium virguliforme* virus 1, *Fusarium virguliforme* virus 2 (FvV1 and FvV2), *Fusarium circinatum* mitovirus 1, *Fusarium circinatum* mitovirus 2-1 and *Fusarium circinatum* mitovirus 2-2 (FcMV1, FcMV2-1 and FcMV2-2) having same effects on *Fusarium boothi*, *Fusarium virguliforme* and *Fusarium circinatum* respectively (Marvelli et al., 2014; Mizutani et al., 2018; Muñoz-Adalia et al., 2016).

**Conclusions and Recommendations**

*Fusarium* is an important genus among fungi including different plant as well as human pathogenic species. They not only cause infection but are also responsible for different mycotoxins that are toxic for both animals and humans. There is a dire need to control this menace so that losses can be minimized and to this end different control strategies can be employed to manage and control this fungus.

**Novelty Statement**

An up to date comprehensive review about *Fusarium* spp. For the first time in this review, mycotoxins and diseases caused by *Fusarium* spp. are discussed. All the possible control strategies for controlling this pathogen are discussed with special reference to biological control, an environmentally safe method. All the information is tabulated for the ease of students and researchers.

**Author’s Contribution**

**Saba Shabeer:** Data collection, drafting the article, revision of the article.

**Riffat Tahira:** Revision of the article.

**Atif Jamal:** Conception of the work, revision of the article and final approval.

**Conflict of interest**

The authors have declared no conflict of interest.

**References**

Abd-Elsalam, K.A., I.N. Aly, M.A. Abdel-Satar, M.S. Khalil and J.A. Verreet. 2003. PCR identification of *Fusarium* genus based on
nuclear ribosomal-DNA sequence data. Afr. J. Biotechnol., 4: 82-88. https://doi.org/10.5897/AJB2003.000-1016

Afãnide, B., S.A. Mabadeje and S.H.Z. Naqvi. 1976. Gibberella baccata, the perfect state of Fusarium lateritium in Nigeria. Mycologia, 5: 1108-1111. https://doi.org/10.1080/00275514.1976.12019994

Agrios, G.N., 1997. Plant pathology, 4th edition, Academic Press, San Diego, CA.

Alabouvette, C., B. Schippers, P. Lemanceau and P.A.H.M. Bakker. 1998. Biological control of Fusarium wilts. In: Plant-microbe interactions and biological control. G.J. Boland and L.D. Kuykendall (eds.). Marcel Dekker Inc., New York. pp. 15-36.

Alvarez, A.M. and W.T. Nishijima. 1987. Postharvest diseases of papaya. Plant Dis., 8: 681-686. https://doi.org/10.1094/PD-71-0681

Aoki, T. and K. O'Donnell. 1999. Morphological characterization of Gibberellacoronica sp. nov., obtained through mating experiments of Fusarium pseudograminearum. Mycoscience, 6: 443-453. https://doi.org/10.1007/BF02461021

Bakker, M.G., D.W. Brown, A.C. Kelly, H.S. Kim, C.P. Kurtzman, S.P. Mccormick, K.L. O'Donnell, R.H. Proctor, M.M. Vaughan and T.J. Ward. 2018. Fusarium mycotoxins: A trans-disciplinary overview. Can. J. Plant Pathol., 2: 161-171. https://doi.org/10.1080/07060661.2018.1433720

Bandyopadhyay, R., M. Mwangi, S.O. Aigbe and J.F. Leslie. 2006. Fusarium species from the cassava root rot complex in West Africa. Phytopathology, 6: 673-676. https://doi.org/10.1094/PHYTO-96-0673

Chen, L.Y., X.L. Tian and B. Yang. 1990. A study on the inhibition of rat myocardium glutathione peroxidase and glutathione reductase by moniliformin. Mycopathologia, 2: 119-124. https://doi.org/10.1007/BF00447001

Chu, Y.M., J.J. Jeon, S.J. Yea, Y.H. Kim, S.H. Yun, Y.W. Lee and K.H. Kim. 2004. Complexity of dsRNA mycovirus isolated from Fusarium graminearum. Virus genes, 1: 135-143. https://doi.org/10.1023/B:VIRU.0000012270.67302.35

Cook, R.J., 1967. Gibberellaavenacea sp. n., perfect stage of Fusarium roseum f. sp. Cerealis Avenaceum. Phytopathology, 7: 732-736.

Crowhurst, R.N., F.Y. King, B.T. Hawthorne, F.R. Sanderson and Y. Choi-Pheng. 1995. RAPD characterization of Fusarium oxysporum associated with wilt of angasana (Pterocarpus indicus) in Singapore. Mycol.
Fusarium species impact on crops

June 2021 | Volume 34 | Issue 2 | Page 288

Res., 1: 14-18. https://doi.org/10.1016/S0953-7562(09)80310-9

Darissa, O., G. Adam and W. Schäfer. 2012. A dsRNA mycovirus causes hypovirulence of Fusarium graminearum to wheat and maize. Eur. J. Plant Pathol., 1: 181-189. https://doi.org/10.1007/s10658-012-9977-5

Davis, R., F. Kegel, W. Sills and J. Farrai. 1989. Fusarium ear rot of corn. California Agric., 6: 4-5.

De Hoog, G.S., J. Guarro, J. Gene and M.J. Figueras. 2000. Atlas of clinical fungi. Centraalbureauvoor Schimmelcultures, Utrecht, The Netherlands, pp. 276-282.

de Vega-Bartol, J.J., R. Martín-Dominguez, B. Ramos, M.A. García-Sánchez and J.M. Díaz-Mínguez. 2011. New virulence groups in Fusarium oxysporum f.sp. phaseoli: the expression of the gene coding for the transcription factor ftf1 correlates with virulence. Phytopathology, 4: 470-479. https://doi.org/10.1094/PHYTO-09-10-0252

Delaney, T.P., S. Uknes, B. Vernooij, L. Friedrich, K. Weymann, T. Gaffney, M. Gut-Rella, H. Kessmann, E. Ward and J. Ryals. 1994. A central role of salicylic acid in plant disease resistance. Science, 5188: 1247-1250. https://doi.org/10.1126/science.266.5188.1247

Desjardins, A.E. and R.D. Plattner. 2000. Fumonisins B1-nonproducing strains of Fusarium verticillioides cause maize (Zea mays) ear infection and ear rot. J. Agric. Food Chem., 11: 5773-5780. https://doi.org/10.1021/jf000619k

Desjardins, A.E., 2006. Fusarium mycotoxins: chemistry, genetics, and biology. Am. Phytopathol. Soc. (APS Press), USA.

Dita, M.A., P.V.I. Luis and M.D.L.P. Einar. 2014. Technical Manual Prevention and diagnostic of Fusarium Wilt (Panama disease) of banana caused by Fusarium oxysporum f. sp. Cubense. Trop. Race, 4 (TR4).

Doohan, F.M., D.W. Parry and P. Nicholson. 1999. Fusarium ear blight of wheat: the use of quantitative PCR and visual disease assessment in studies of disease control. Plant Patho., United Kingdom. Available at: http://agris.fao.org/agris-search/search.do?recordID=GB1999007777, https://doi.org/10.1046/j.1365-3059.1999.00342.x

Dutkiewicz, J., B. Mackiewicz, M.K. Lemieszek, M. Golec and J. Milanowski. 2016. Pantoeaagglomerans: A mysterious bacterium of evil and good. Part IV. Beneficial effects. Annals of Agricultural and Environmental Medicine. https://doi.org/10.5604/12321966.1203879

Dweba, C.C., S. Figlan, H.A. Shimelis, T.E. Motaung, S. Sydenham, L. Mwadzingeni and T.J. Tsilo. 2017. Fusarium head blight of wheat: Pathogenesis and control strategies. Crop Prot., 91: 114-122. https://doi.org/10.1016/j.cropro.2016.10.002

Early, R., 2009. Pathogen control in primary production: crop foods. In: Foodborne Pathogens. 2nd Edition, Woodhead Publishing, UK. pp. 205-279. https://doi.org/10.1533/9781845696337.1.205

Elmer, W.H., 1996. Fusarium fruit rot of pumpkin in Connecticut. Plant Dis., 2: 131-135. https://doi.org/10.1094/PD-80-0131

Evidente, A., C. Amalfitano, R. Pengue and C. Alтомare. 1999. High performance liquid chromatography for the analysis of fusapyrone and deoxyfusapyrone, two antifungal α pyrones from Fusarium semitectum. Natl. Toxins, 4: 133-137. https://doi.org/10.1002/(SICI)1522-7189(199907/08)7:4<133::AID-AID-NT60>3.0.CO;2-I

Ferrer, C., F. Colom, S. Frasés, E. Mulet, J.L. Abad and J.J. Alió. 2001. Detection and identification of fungal pathogens by PCR and by ITS2 and 5.8 S ribosomal DNA typing in ocular infections. J. Clin. Microbiol., 8: 2873-2879. https://doi.org/10.1128/JCM.39.8.2873-2879.2001

Flood, J., 2006. A review of Fusarium wilt of oil palm caused by Fusarium oxysporum f. sp. elaeidis. Phytopathology, 6: 660-662. https://doi.org/10.1094/PHYTO-96-0660

Fravel, D.R. and C.A. Engelkes,1994. Biological management. In: Epidemiology and management of root diseases. Springer, Berlin, Heidelberg. pp.293-308. https://doi.org/10.1007/978-3-642-85063-9_10

Gachango, E., L.E. Hanson, A. Rojas, J.J. Hao and W.W. Kirk. 2012. Fusarium spp. causing dry rot of seed potato tubers in Michigan and their sensitivity to fungicides. Plant Dis., 12: 1767-1774. https://doi.org/10.1094/PDIS-11-11-0932-RE

Geiser, D.M., M.L. Ivey, G. Hakiza, J.H. Juba and S.A. Miller. 2005. Gibberellaxylarioides (anamorph: Fusarium xylarioides), a causative
agent of coffee wilt disease in Africa, is a previously unrecognized member of the G. fujikuroi species complex. Mycologia, 1: 191-201. https://doi.org/10.3852/mycologia.97.1.191

Gilbert, J. and A. Tekauz. 1995. Effects of fusarium head blight and seed treatment on germination, emergence, and seedling vigour of spring wheat. Can. J. Plant Pathol., 3: 252-259. https://doi.org/10.1080/07060669509500687

Gilbert, J., A. Tekauz and S.M. Woods. 1997. Effect of storage on viability of Fusarium head blight-affected spring wheat seed. Plant Dis., 81: 159-162. https://doi.org/10.1094/PDIS.1997.81.2.159

Gordon, T.R., 2006. Pitch canker disease of pines. Phytopathology, 6: 657-659. https://doi.org/10.1094/PHYTO-96-0657

Gordon, T.R., S.C. Kirkpatrick, B.J. Aegeter, D.L. Wood and A.J. Storer. 2006. Susceptibility of Douglas fir (Pseudotsugamenziesii) to pitch canker, caused by Gibberellacircinata (anamorph= Fusarium circinatum). Plant Pathol., 2: 231-237. https://doi.org/10.1111/j.1365-3059.2006.01351.x

Gupta, C.P., A. Sharma, R.C. Dubey and D.K. Maheshwari. 1999. Pseudomonas aeruginosa (GRC~ 1) as a strong antagonist of Macrophominaphaseolina and Fusarium oxysporum. Cytobios-Cambridge, pp. 183-189.

Häni, F., 1981. ZurBiologie und Bekämpfung von FusariosenbeiWeizen und Roggen. J. Phytopathol., 1: 44-87. https://doi.org/10.1007/j.1439-0434.1981.tb03289.x

Hansen, A.J., 1966. Fusaria as agents of cacao green point cushion gall in the Caribbean and in Latin America. Plant Dis. Rep., 50: 229-233.

Holliday, P., 1980. Fungus diseases of tropical crops cambridge. pp. 147.

Jurgenson, J.E., K.A. Zeller and J.F. Leslie. 2002. Expanded genetic map of Gibberella moniliformis (Fusarium verticillioides). Appl. Environ. Microbiol., 4: 1972-1979. https://doi.org/10.1128/AEM.68.4.1972-1979.2002

Kachuei, R., M.H. Yadegari, N. Safaie, A. Ghiasian, F. Noorbakhsh, V. Piranfar and S. Rezaie. 2015. PCR-RFLP patterns for the differentiation of the Fusarium species in virtue of ITS rDNA. Curr. Med. Mycol., 1: 4. https://doi.org/10.18869/acadpub.cmm.1.1.4

Karlovsky, P., M. Suman, F. Berthiller, J. De Meester, G. Eisenbrand, I. Perrin, I.P. Oswald, G. Speijers, A. Chiodini, T. Recker and P. Dussort. 2016. Impact of food processing and detoxification treatments on mycotoxin contamination. Mycotoxin Res., 4: 179-205. https://doi.org/10.1007/s12550-016-0257-7

Kawchuk, L.M., J.D. Holley, D.R. Lynch and R.M. Clear. 1994. Resistance to thiabendazole and thiophanate-methyl in Canadian isolates of Fusarium sambucinum and Helminthosporiumsolani. Am. Potato J., 3: 185-192. https://doi.org/10.1007/BF02849053

Kazan, K., D.M. Gardiner and J.M. Manners. 2012. On the trail of a serial killer: Recent advances in Fusarium graminearum pathogenomics and host resistance. Mol. Plant Pathol., 4: 399-413. https://doi.org/10.1111/j.1364-3703.2011.00762.x

Keller, S.E. and T.M. Sullivan. 1996. Liquid culture methods for the production of fusaminoisin. In: Fumonisins in Food. Springer, Boston, MA. pp. 205-212. https://doi.org/10.1007/978-1-4899-1379-1_18

Khan, M.K., A. Pandey, T. Athar, S. Choudhary, R. Deval, S. Gezgin and M.R. Omay. 2020. Fusarium head blight in wheat: contemporary status and molecular approaches. Biotech, 4: 1-17. https://doi.org/10.1007/s13205-020-2158-x

Kim, K.K., J.G. Kang, S.S. Moon and K.Y. Kang. 2000. Isolation and identification of antifungal N-butylbenzenesulphonamide produced by Pseudomonas sp. AB2. J. Antibiotics, 2: 131-136. https://doi.org/10.7164/antibiotics.53.131

Knights, E.J., 2004. Chickpea overview. In: Encyclopedia of grain science, C.W. Wrigley, H. Corke and C.E. Walker (ed). Academic press. 1: 280–287. https://doi.org/10.1016/B0-12-765490-9/00034-3

Kosmidis, C. and D.W. Denning. 2017. Opportunistic and systemic fungi. In: Infectious diseases, Elsevier, pp. 1681-1709. https://doi.org/10.1016/B978-0-7020-6285-8.00189-1

Krauss, U. and A. Johanson. 2000. Recent advances in the control of crown rot of banana in the Windward Islands. Crop Protection, 3: 151-159. https://doi.org/10.1016/S0261-2194(99)00097-6

Larena, I., and P. Melgarejo. 1996. Biological Control of Monilialaxa and Fusarium oxysporum f. sp. Lycopersiciby a Lytic Enzyme-Producing Penicillium purpurogenum. Biol.
Fusarium species impact on crops

June 2021 | Volume 34 | Issue 2 | Page 290

https://doi.org/10.1006/bcon.1996.0046

Leslie, J.F., B.A. Summerell, S. Bullock and F.J. Doc. 2005. Description of Gibberellasacchari and neotypification of its anamorph Fusarium sacchari. Mycologia, 3: 718-724. https://doi.org/10.3852/mycologia.97.3.718

Li, P., H. Zhang, X. Chen, D. Qiu and L. Guo. 2015. Molecular characterization of a novel hypovirus from the plant pathogenic fungus Fusarium graminearum. Virology, 481: 151-160. https://doi.org/10.1016/j.virol.2015.02.047

Li, P., Y. Lin, H. Zhang, S. Wang, D. Qiu and L. Guo. 2016. Molecular characterization of a novel mycovirus of the family Tymoviridae isolated from the plant pathogenic fungus Fusarium graminearum. Virology, 489: 86-94. https://doi.org/10.1016/j.virol.2015.12.004

Liew, E.C.Y., F. Rondonuwu, A. Pinaria, D.T. Sembel, B.A. Summerell and L.W. Burgess. 2004. Fusarium stem rot of vanilla in North Sulawesi. In: Phytopathology, Vol. 94, pp: S61-S61. 3340. Pilot Knob Road, St Paul, Mn 55121 Usa: Am. Phytopathol. Soc.,

Logrieco, A., A. Moretti, G. Castella, M. Kostecki, P. Golinski, A. Ritienn and J. Chelkowski. 1998. Beauvericin Production by Fusarium Species. Appl. Environ. Microbiol., 8: 3084-3088. https://doi.org/10.1128/AEM.64.8.3084-3088.1998

Loi, M., F. Fanelli, V. Liuzzi, A. Logrieco and G. Mulè, 2017. Mycotoxin biotransformation by native and commercial enzymes: Present and future perspectives. Toxins, 4: 111. https://doi.org/10.3390/toxins9040111

Ma, L.J., D.M. Geiser, R.H. Proctor, A.P. Rooney, K. O'Donnell, F. Trail, D.M. Gardiner, J.M. Manners and K. Kazan. 2013. Fusarium pathogenomics. Annu. Rev. Microbiol., 67: 399-416. https://doi.org/10.1146/annurev-micro-092412-155650

Manners, J.G., 1993. Principles of plant pathology. Cambridge University Press, Cambridge.

Manocha, M.S. and V. Govindsamy. 1998. Chitinolytic enzymes of fungi and their involvement in biocontrol of plant pathogens. Plant–Microbe Interact. Biol. Control.

Marasas, W.F.O., R.C. Ploetz, M.J. Wingfield, B.D. Wingfield and E.T. Steenkamp. 2006. Mango malformation disease and the associated Fusarium species. Phytopathology, 6: 667-672. https://doi.org/10.1094/PHYTO-96-0667

Marin, S., A.J. Ramos, G. Cano-Sancho and V. Sanchis, 2013. Mycotoxins: Occurrence, toxicology, and exposure assessment. Food and Chem. Toxicol., 60: 218-237. https://doi.org/10.1016/j.fct.2013.07.047

Marin, S., V. Sanchis, D. Sanz, I. Castel, A.J. Ramos, R. Canela and N. Magan. 1999. Control of growth and fumonisin B1 production by Fusarium verticillioides and Fusarium proliferatum isolates in moist maize with propionate preservatives. Food Additives Contam., 12: 555-563. https://doi.org/10.1080/026520399283696

Marvelli, R.A., H.A. Hobbs, S. Li, N.K. McCoppin, L.L. Domier, G.L. Hartman and D.M. Eastburn. 2014. Identification of novel double-stranded RNA mycoviruses of Fusarium virguliforme and evidence of their effects on virulence. Arch. Virol., 2: 349-352. https://doi.org/10.1007/s00705-013-1760-1

Mauch-Mani, B. and J.P. Métraux. 1998. Salicylic acid and systemic acquired resistance to pathogen attack. Ann. Bot., 5: 535-540. https://doi.org/10.1006/anbo.1998.0726

McMullen, M., R. Jones and D. Gallenberg. 1997. Scab of wheat and barley: A re-emerging disease of devastating impact. Plant Dis., 12: 1340-1348. https://doi.org/10.1094/PDIS.1997.81.12.1340

Michielse, C.B. and M. Rep. 2009. Pathogen profile update: Fusarium oxysperum. Mol. Plant Pathol., 3: 311-324. https://doi.org/10.1111/j.1364-3703.2009.00538.x

Mishra, P.K., R.T. Fox and A. Culham. 2003. Development of a PCR-based assay for rapid and reliable identification of pathogenic Fusaria. FEMS Microbiol. Lett., 2: 329-332. https://doi.org/10.10111/j.1574-6968.2003.tb11537.x

Mizutani, Y., A. Abraham, K. Uesaka, H. Kondo, H. Suga, N. Suzuki and S. Chiba, 2018. Novel Mitoviruses and a Unique Tymo-Like Virus in Hypovirulent and Virulent Strains of the Fusarium Head Blight Fungus, Fusarium boothii. Viruses, 11: 584. https://doi.org/10.3390/v10110584

Mulè, G., A. Logrieco, G. Stea and A. Bottalico. 1997. Clustering of trichothece-producing Fusarium strains determined from 28S ribosomal DNA sequences. Appl. Environ. Microbiol., 5: 1843-1846. https://doi.org/10.1128/AEM.64.8.3084-3088.1998
Fusarium species impact on crops

June 2021 | Volume 34 | Issue 2 | Page 291

- Mulè, G., A. Susca, G. Stea and A. Moretti, 2004. A species-specific PCR assay based on the calmodulin partial gene for identification of Fusarium verticillioides, F. proliferatum and F. subglutinans. Eur. J. Plant Pathol., 5-6: 495-502. https://doi.org/10.1023/B:EJPP.0000032389.84048.71

- Munkvold, G.P., 2017. Fusarium species and their associated mycotoxins. In: Mycotoxigenic Fungi. Humana Press, New York, NY. pp. 51-106. https://doi.org/10.1007/978-1-4939-6707-0_4

- Muñoz-Adalia, E.J., J.A. Flores-Pacheco, P. Martínez-Álvarez, J. Martín-García, M. Fernández and J.J. Diez. 2016. Effect of mycoviruses on the virulence of Fusarium circinatum and laccase activity. Physiol. Mol. Plant Pathol., 94: 8-15. https://doi.org/10.1016/j.pmpp.2016.03.002

- Navas-Cortés, J.A., B. Hau and R.M. Jiménez-Díaz. 1998. Effect of sowing date, host cultivar, and race of Fusarium oxysporum f. sp. ciceris on development of Fusarium wilt of chickpea. Phytopathology, 12: 1338-1346. https://doi.org/10.1094/PHYTO.1998.88.12.1338

- Nelson, P.E., R.D. Plattner, D.D. Shackelford and A.E. Desjardins, 1992. Fumonisin B1 production by Fusarium species other than F. moniliforme in section Liseola and by some related species. Appl. Environ. Microbiol., 3: 984-989. https://doi.org/10.1128/AEM.58.3.984-989.1992

- Nicholson, P., D.R. Simpson, G. Weston, H.N. Rezanoor, A.K. Lees, D.W. Parry and D. Joyce, 1998. Detection and quantification of Fusarium culmorum and Fusarium graminearum in cereals using PCR assays. Physiol. Mol. Plant Pathol., 1: 17-37. https://doi.org/10.1006/pmpp.1998.0170

- Nucci, M. and E.J. Anaissie. 2009. Hyalohyphomycosis. In: Clinical mycology. Churchill Livingstone, pp. 309-327. https://doi.org/10.1016/B978-1-4160-5680-5.00013-X

- Nuss, D.L., 2005. Hypovirulence: Mycoviruses at the fungal–plant interface. Nat. Rev. Microbiol., 8: 632. https://doi.org/10.1038/nrmicro1206

- O'Donnell, K., 1992. Ribosomal DNA internal transcribed spacers are highly divergent in the phytopathogenic ascomycete Fusarium sambucinum (Gibberellapulicaris). Curr. Genet., 3: 213-220. https://doi.org/10.1007/BF00351728

- Ogawa, K., N. Yoshida, W. Gesnara, C.A. Omumasaba and C. Chamuswarng. 2000. Hybridization and breeding of the benomyl resistant mutant, Trichoderma harzianum antagonized to phytopathogenic fungi by protoplast fusion. Biosci. Biotechnol. Biochem., 4: 833-836. https://doi.org/10.1271/bbb.64.833

- Oliveira, D.P. and J.L. Pereira. 1983. Importanciapatologicarelativa de Fusarium e Phytophthora nacultura da pimenta-do-reinona Bahia, Brasil. Revista Theobroma.

- Ploetz, R.C., 2006. Fusarium wilt of banana is caused by several pathogens referred to as Fusarium oxysporum f. sp. cubense.
Phytopathology, 6: 653-656. https://doi.org/10.1094/PHYTO-96-0653

Poppenberger, B., F. Berthiller, D. Lucyszyn, T. Sieberer, R. Schuhmacher, K. Krska, K. Kuchler, J. Glossl, C. Luschnig and G. Adam, 2003. Detoxification of the Fusarium mycotoxin deoxynivalenol by a UDP-glucosyltransferase from Arabidopsis thaliana. J. Biol. Chem., 48: 47905-47914. https://doi.org/10.1074/jbc.M307552200

Pusateri, A.E. and D.C. Kenison, 1993. Measurement of zeronal in plasma from three blood vessels in steers implanted with zeronal. J. Anim. Sci., 2: 415-419. https://doi.org/10.2527/1993.712415x

Qi, Y.X., J.J. Pu, X. Zhang, H. Zhang, Y. Lu, Q.F. Yu, H.Q. Zhang and Y.X. Xie, 2013. First report of dieback of mango caused by Fusarium decemcellulare in China. J. Phytopathol., 10: 735-738. https://doi.org/10.1111/jph.12117

Rai, B. and R.S. Upadhyay, 1982. Gibberella indica: The perfect state of Fusariumudum. Mycologia, 2: 343-346. https://doi.org/10.1080/00275514.1982.12021513

Rheeder, J.P., W.F. Marasas and H.F. Vismer, 2002. Production of fumonisin analogs by Fusarium species. Appl. Environ. Microbiol., 5: 2101-2105. https://doi.org/10.1128/AEM.68.5.2101-2105.2002

Romberg, M.K. and R.M. Davis, 2007. Host range and phylogeny of Fusarium solani f. sp. eumartii from potato and tomato in California. Plant Dis., 5: 585-592. https://doi.org/10.1094/PDIS-91-5-0585

Rutherford, M.A., 2006. Current knowledge of coffee wilt disease, a major constraint to coffee production in Africa. Phytopathology, 6: 663-666. https://doi.org/10.1094/PHYTO-96-0663

Ryu, D. and L.B. Bullerman, 1999. Effect of cycling temperatures on the production of deoxynivalenol and zearalenone by Fusarium graminearum NRRL 5883. J. Food Prot., 12: 1451-1455. https://doi.org/10.4315/0362-028X-62.12.1451

Ryu, D., C. Munimbazi and L.B. Bullerman, 1999. Fumonisin B1 production by Fusarium moniliforme and Fusarium proliferatum as affected by cycling temperatures. J. Food Prot., 12: 1456-1460. https://doi.org/10.4315/0362-028X-62.12.1456

Salvalaggio, A.E. and A.D.C. Ridao, 2013. First report of Fusarium proliferatum causing rot on garlic and onion in Argentina. Plant Dis., 4: 556-556. https://doi.org/10.1094/PDIS-05-12-0507-PDN

Schilling, A.G., E.M. Moller and H.H. Geiger, 1996. Polymerase chain reaction-based assays for species-specific detection of Fusarium culmorum, F. graminearum, and F. avenaceum. Phytopathology, 5: 515-522. https://doi.org/10.1094/Phyto-86-515

Schönbeck, F., G. Grunewaldt-Stöcker and H. von Alten, 1994. Mycorrhizae. In: Epidemiology and management of root diseases. Springer, Berlin, Heidelberg, pp. 65-81. https://doi.org/10.1007/978-3-642-85063-9_3

Secor, G.A. and N.C. Gudmestad, 1999. Managing fungal diseases of potato. Can. J. Plant Pathol., 3: 213-221. https://doi.org/10.1080/0706066990501184

Sheraliw, A.S. and K.V. Bukharov, 2001. Fusarium species infecting agricultural and weed plants in Uzbekistan. Mikologiyai Fitopatologiya, 2: 44-47.

Sneh, B., 1998. Use of non-pathogenic or hypovirulent fungal strains to protect plants against closely related fungal pathogens. Biotechnol. Adv., 1: 1-32. https://doi.org/10.1016/S0734-9751(97)00044-X

Stockmann-Juvala, H. and K. Savoilainen, 2008. A review of the toxic effects and mechanisms of action of fumonisin B1. Hum. exp. Toxicol., 11: 799-809. https://doi.org/10.1177/0960327108099525

Suga, H. and M. Hyakumachi, 2004. Genomics of phytopathogenic Fusarium. In: Applied Mycology and Biotechnology. Elsevier, pp: 161-189. https://doi.org/10.1016/S1874-5334(04)80009-1

Summerell, B.A., B. Salleh and J.F. Leslie, 2003. A utilitarian approach to Fusarium identification. Plant Dis., 2: 117-128. https://doi.org/10.1094/PDIS.2003.87.2.117

Sumner, D.R., 1994. Cultural management. In: Epidemiology and Management of Root Diseases. Springer, Berlin, Heidelberg, pp: 309-333. https://doi.org/10.1007/978-3-642-85063-9_11

Sweeny, M.J. and A.D. Dobson, 1998. Mycotoxin production by Aspergillus, Fusarium and Penicillium species. Int. J. Food Microbiol.,
3: 141-158. https://doi.org/10.1016/S0168-1605(98)00112-3

Thiel, P.G., W.F. Marasas, E.W. Sydenham, G.S. Shephard, W.C. Gelderblom and J.J. Nieuwenhuis. 1991. Survey of fumonisin production by \textit{Fusarium} species. Appl. Environ. Microbiol., 4: 1089-1093. https://doi.org/10.1128/AEM.57.4.1089-1093.1991

Thrane, U., 2001. Development in the taxonomy of \textit{Fusarium} species based on secondary metabolites. In: \textit{Fusarium: Paul E. Nelson Memorial Symposium}. APS Press. pp. 29-49.

Tzatzarakis, M., A.M. Tsatsakis, A. Liakou and D.J. Vakalounakis. 2000. Effect of common food preservatives on mycelial growth and spore germination of \textit{Fusarium oxysporum}. J. Environ. Sci. Hlth Part B., 4: 527-537. https://doi.org/10.1080/03601230009373288

Ventura, J.A., 1994. Pineapple fusariosis: Characterization of the pathogen, epidemiology of disease, resistance and micropropagation of host in vitro. Doctoral dissertation, Ph. D. thesis, Federal University of Viçosa. Viçosa, Minas Gerais.

Vishwakarma, S., P. Kumar, A. Singh and A. Kumar. 2013. Pokkahboeng: An emerging disease of sugarcane. J. Plant Pathol. Microbiol., 170: 2.

Viswanathan, R., M. Poongothai and P. Malathi. 2011. Pathogenic and molecular confirmation of \textit{Fusarium sacchari} causing wilt in sugarcane. J. Environ. Sci. Hlth Part B., 4: 527-537. https://doi.org/10.1080/01638761.2011.602959

Waite, B.H., 1954. Vascular disease of abaca or Manila hemp in Central America. Plant Dis. Rep., 38: 575-578.

Walker, J.C., 1971. \textit{Fusarium} wilt of tomato, APS Publisher, Madison, USA.

Wall, J.M. and D. Brayford. 1990. \textit{Fusarium} diseases in the tropics. Int. J. Pest Manage., 3: 181-194. https://doi.org/10.1080/09670879009371470

Wang, S., H. Kondo, L. Liu, L. Guo and D. Qiu, 2013. A novel virus in the family Hypoviridae from the plant pathogenic fungus \textit{Fusarium graminearum}. Virus Res., 1-2: 69-77. https://doi.org/10.1016/j.virusres.2013.03.002

Williams, K.J., J.I. Dennis, C. Smyl and H. Wallwork, 2002. The application of species-specific assays based on the polymerase chain reaction to analyse \textit{Fusarium} crown rot of durum wheat. Aust. Plant Pathol., 2: 119-127. https://doi.org/10.1071/AP01079

Windels, C.E., 1991. Current status of \textit{Fusarium} taxonomy. Phytopathology, 9: 1048-1051.

Wulff, E.G., J.L. Sorensen, M. Lübeck, K.F. Nielsen, U. Thrane and J. Torp. 2010. \textit{Fusarium} spp. associated with rice Bakanae: ecology, genetic diversity, pathogenicity and toxigenicity. Environ. Microbiol., 3: 649-657. https://doi.org/10.1111/j.1462-2920.2009.02105.x

Yates, I.E., F. Meredith, W. Smart, C.W. Bacon and A.J. Jaworski. 1999. Trichoderma viride suppresses fumonisin B1 production by \textit{Fusarium moniliforme}. J. Food Prot., 11: 1326-1332. https://doi.org/10.4315/0362-028X-62.11.1326

Young, J.C., 1986. Reduction in levels of deoxynivalenol in contaminated corn by chemical and physical treatment. J. Agric. Food Chem., 3: 465-467. https://doi.org/10.1021/jf00069a022

Young, J.C., L.M. Subryan, D. Potts, M.E. McLaren and F.H. Gobran. 1986. Reduction in levels of deoxynivalenol in contaminated wheat by chemical and physical treatment. J. Agric. Food Chem., 3: 461-465. https://doi.org/10.1021/jf00069a021

Yu, J., R.H. Proctor, D.W. Brown, K. Abe, K. Gomi, M. Machida, F. Hasegawa, W.C. Nierman, D. Bhatnagar and T.E. Cleveland. 2004. Genomics of economically significant Aspergillus and \textit{Fusarium} species. Appl. Mycol. Biotechnol., 4: 249-283. https://doi.org/10.1016/S1874-5334(04)80013-3

Yu, J.S., K.M. Lee, M.I. Son and K.H. Kim. 2011. Molecular characterization of \textit{Fusarium graminearum} virus 2 isolated from \textit{Fusarium graminearum} strain 98-8-60. Plant Pathol. J., 3: 285-290. https://doi.org/10.5423/PPJ.2011.27.3.285

Zhu, Y., Y.I. Hassan, C. Watts and T. Zhou. 2016. Innovative technologies for the mitigation of mycotoxins in animal feed and ingredients. A review of recent patents. Anim. Feed Sci. Technol., 216: 19-29. https://doi.org/10.1016/j.anifeedsci.2016.03.030