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Fusarium: Historical and Continued Importance

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Abstract

Historically, *Fusarium* has been important because: (i) taxonomy of *Fusarium* species has been a controversial issue, (ii) *Fusarium* species are among the most important plant pathogens in the world, and (iii) many *Fusarium* species produce mycotoxins that cause animal and human diseases. The genus *Fusarium* was introduced by Link in 1809. “Die Fusarien” was published by Wollenweber and Reinking in 1935, described 65 species, 55 varieties, and 22 forms of *Fusarium*. In 1945, Snyder and Hansen reduced number of species of *Fusarium* to nine. In 1990s, the application of phylogenetic species concept based on the DNA sequencing resulted in introducing new species of *Fusarium* that cannot be distinguished morphologically. In 2006, Leslie and Summerell integrated the morphological, biological, and phylogenetic species concepts and published “The *Fusarium* Laboratory Manual,” which provides details of identification of 70 *Fusarium* species. Although considerable research studies on *Fusarium* have been accomplished in the past 200 years, yet *Fusarium* diseases continue to be among the most important plant diseases. *Fusarium* fungi are the most widespread in cereal-growing areas of the world and produce a diversity of mycotoxins, including zearalenone, fumonisin, moniliformin, and trichothecenes, which cause various disorders, including cancer, in animals and humans.

Keywords: *Fusarium*, taxonomy, fungi, plant diseases, mycotoxins

1. Introduction

The genus *Fusarium* was introduced by Link in 1809 [1]. However, *Fusarium* received more attention when “Die Fusarien” was published by Wollenweber and Reinking in 1935 [2]. In the past 80 years, tremendous investigations have been carried out on the taxonomy, biology, and mycotoxins of *Fusarium* species [3–5]. Although Wollenweber and Reinking described 65 species, 55 varieties, and 22 forms of *Fusarium* in 1935 [2], Snyder and Hansen reduced number of species of *Fusarium* to nine [6]. During 1940–1980, several mycologists developed different

taxonomy of *Fusarium*, but none of them received a global agreement. During 1980s, *Fusarium* taxonomists in the world collaborated to offer a unique agreement on *Fusarium* taxonomy. In 1990s, however, the application of phylogenetic species concept based on the DNA sequencing resulted in introducing new species of *Fusarium* that often cannot be distinguished morphologically. In 2006, Leslie and Summerell published “The *Fusarium* Laboratory Manual” and described 70 *Fusarium* species [3].

Fusarium species are among the most common and widespread plant pathogens in the world and are of great economic importance [4]. Every plant pathologist, mycologist, agronomist, and horticulturist encounters them in the course of work. They are serious pathogens on a wide range of crops. In spite of worldwide investigations on *Fusarium* in the past 200 years, *Fusarium* diseases continue to be among most important plant diseases and cause widespread crop losses throughout the world [4, 7].

Several *Fusarium* species produce mycotoxins, which cause various disorders, including cancer in animals and humans [5]. Zearalenone, fumonisin, moniliformin, and trichothecenes are among most important *Fusarium* mycotoxins, especially in grains [5]. The objective of this chapter is to provide details of *Fusarium* taxonomy, pathology, and mycotoxins.

2. Taxonomy

The genus *Fusarium* was introduced in 1809 [1]. During 1809–1935, much of the works on *Fusarium* were focused on identification of *Fusarium* species and diagnosis of *Fusarium* diseases. In the past 100 years, the taxonomy of *Fusarium* has undergone a number of changes, which is adapted and “The *Fusarium* Laboratory Manual” [3].

2.1. Wollenweber and Reinking

The basis for all modern taxonomic systems of *Fusarium* species is the work of Wollenweber and Reinking, which was published in “Die Fusarien” in Germany. In this publication, 16 sections, 65 species, 55 varieties, and 22 forms of *Fusarium* were introduced, which were separated based on the morphological differences [2]. Prior to this publication, about a thousand *Fusarium* species had been described, often a different species for every host. Wollenweber and Reinking offered an order to a chaotic situation of *Fusarium* taxonomy. In their taxonomic system, each section contained species that were united by critical morphological characteristics (e.g., macroconidia morphology and pigment). Each section contained only a few species. Other taxonomists used the sections created by Wollenweber and Reinking to develop their taxonomic systems.

2.2. Snyder and Hansen

During 1940s and 1950s, Snyder and Hansen in the United States (US) developed a new taxonomy system and reduced number of species of *Fusarium* to nine [6, 8, 9]. Their identification was based on using cultures derived from single spores. The Snyder and Hansen species taxonomy was easy to use and identify any *Fusarium* isolate to species level.

2.3. Gordon

Gordon published a number of papers on *Fusarium* species collected from Canada [10–12]. He used *Fusarium* taxonomy system developed by Wollenweber and Reinking with some concepts of Snyder and Hansen system.

2.4. Messiaen and Cassini

These French scientists developed a *Fusarium* taxonomy system based on Snyder and Hansen system [13]. They used varieties for the subspecific level instead of cultivars, which was used by Snyder and Hanson.

2.5. Matuo

Matuo was a Japanese scientist who used the system developed by Snyder and Hanson and introduced a new *Fusarium* taxonomy system with 10 species [14].

2.6. Raillo

Raillo, a Russian scientist, published a taxonomic system based on the shape of macroconidia, and the presence of microconidia and chlamydospores [15].

2.7. Bilai

Bilai, a Ukrainian scientist, studied variability in characteristics related to temperature, moisture, and culture media composition and offered her own revision of the taxonomy of the genus *Fusarium* and recommended combining some sections suggested by Wollenweber and Reinking [16, 17].

2.8. Booth

A significant development in the taxonomy of *Fusarium* was made by Booth from England during 1960s and 1970s. He published a monograph “The Genus *Fusarium*” [18], which was a revision of the Wollenweber and Reinking’s system. Booth introduced the use of the morphology of the conidiogenous cells, especially those producing the macroconidia.

2.9. Gerlach and Nirenberg

Based on the taxonomy published in “Die Fusarien,” Gerlach and Nirenberg published their own *Fusarium* taxonomy system in Germany in 1982 [19]. In spite of the criticism of their taxonomic system, their work was a significant step forward in understanding of *Fusarium* taxonomy and many of the suggested species in their system are now accepted.

2.10. Joffe

Joffe, originally a Russian scientist and then in Israel, began his studies on *Fusarium* in Russia in 1940s. He included *Fusarium* isolates collected from Russia, Israel, and some other

countries in his studies and evaluated their taxonomic and mycotoxicological issues. His work was published as a monograph “*Fusarium* Species: Their Biology and Toxicology” [20]. His taxonomic approach was based on the taxonomic systems of Wollenweber and Reinking [2] and Gerlach and Nirenberg [19].

2.11. Nelson, Toussoun and Marasas

Toussoun and Nelson from the United States published a pictorial guide for identification of *Fusarium* species, in which 9 species and 10 cultivars were described [21]. In 1983, Nelson and Toussoun together with W. F. O. Marasas from South Africa published an illustrated manual of *Fusarium* species and described 46 species [22]. Their taxonomic approach began a definitive shift toward a more complicated taxonomy and a larger set of recognized species and away from the nine species of Snyder and Hansen system. This manual has been widely used by scientists.

2.12. 1980s and 1990s

During 1980s, *Fusarium* taxonomists, including Burgess and Summerell from Australia, Gerlach and Nirenberg from Germany, Marasas from South Africa, and Nelson and Toussoun from the US collaborated to offer a unique agreement on *Fusarium* taxonomy based on fungal morphological characteristics. In 1990s, however, the application of phylogenetic species concept to DNA sequencing resulted in introducing new species of *Fusarium* that often cannot be distinguished morphologically. Thus, the relatively unique uniformity of 1980s shifted toward another chaos on *Fusarium* taxonomy.

2.13. Leslie and Summerell

In 2006, Leslie from the United States and Summerell from Australia integrated the morphological, biological, and phylogenetic species concepts and published “The *Fusarium* Laboratory Manual” with 70 species [3]. This manual, which is based on the outcomes of workshops conducted at the Kansas State University, is widely used by mycologists and plant pathologists to identify *Fusarium* isolates.

Although taxonomy of *Fusarium* species has been historically a complex issue, and no unanimous agreement available among the *Fusarium* taxonomists, using morphological characteristics combined by the molecular data minimizes differences in identification of *Fusarium* isolates. As more information is generated, more accurate taxonomic systems are expected to be developed for the identification of species of *Fusarium*.

3. Pathology

The members of genus *Fusarium* can incite diseases in plants, animals, and humans [23]. The mortality rate for human patients with systemic *Fusarium* infection is reported to be greater than 70% [24]. In addition, *Fusarium* species produce secondary metabolites that are associated with plant diseases, as well as with diseases of animals and humans [25, 26]. In this chapter, only *Fusarium* diseases in plants will be discussed.

Fusarium has been known for over 200 years. Despite universal effort on developing effective management of *Fusarium* in plants, *Fusarium* diseases continue to be among the most important plant diseases. *Fusarium* species are among the most widespread fungi in the world and are of great economic importance. Many plant species are affected with at least one *Fusarium* disease [3, 4]. The American Phytopathological Society reported that 81 of 101 economically important plants have at least one *Fusarium* disease (www.apsnet.org/online/common/search.asp). To understand importance of *Fusarium* diseases in plants, **Table 1** was prepared that shows *Fusarium* species, their host plants, and geographical distributions.

<i>Fusarium</i> species	Host plants	Geographic distribution
<i>F. acuminatum</i>	Legumes	Temperate regions
<i>F. andiyazi</i>	Sorghum	Africa, Australia, US
<i>F. anthophilum</i>	Many plant species	Temperate regions
<i>F. avenaceum</i>	Carnations, cereals, legumes	Temperate regions
<i>F. aywerte</i>	Grasses	Australia
<i>F. babinda</i>	Soil	Australia
<i>F. begoniae</i>	<i>Begonia</i> species	Germany
<i>F. brevicatenulatum</i>	Millet, <i>Striga asiatica</i>	Africa
<i>F. bulbicola</i>	Bulb plant species	Europe
<i>F. camptoceras</i>	Banana, cacao	Tropical and subtropical regions
<i>F. circinatum</i>	Conifers	Chile, Japan, Mexico, South Africa, US
<i>F. concentricum</i>	<i>Musa</i> species	Central America
<i>F. crookwellense</i>	Potato, cereals	Temperate regions
<i>F. culmorum</i>	Cereals	Temperate regions
<i>F. decemcellulare</i>	Trees	Tropical regions
<i>F. denticulatum</i>	Sweet potato	Brazil, Cuba, Indonesia, US, Zambia
<i>F. foetens</i>	<i>Begonia</i> species	Germany, Netherlands
<i>F. fujikuroi</i>	Rice	Rice-growing areas
<i>F. globosum</i>	Corn, wheat	Africa, Japan
<i>F. graminearum</i>	Barley, corn, wheat	Worldwide
<i>F. guttiforme</i>	Pineapple	Cuba, South America
<i>F. heterosporum</i>	Millet, other grasses	Africa
<i>F. hostae</i>	<i>Hosta</i> species	South Africa, US
<i>F. konzum</i>	Grasses	US
<i>F. lactis</i>	Fig	US
<i>F. lateritium</i>	Woody plants	Worldwide
<i>F. mangiferae</i>	Mango	Africa, Asia, US
<i>F. musarum</i>	Banana	Panama
<i>F. napiforme</i>	Millet, sorghum	Africa, Argentina, Australia
<i>F. nelsonii</i>	Alfalfa, sorghum	South Africa
<i>F. nisikadoi</i>	Bamboo, wheat	Japan

<i>Fusarium</i> species	Host plants	Geographic distribution
<i>F. nygamai</i>	Sorghum	Arid regions
<i>F. oxysporum</i>	Many plant species	Worldwide
<i>F. phyllophilum</i>	<i>Dracaena</i> and <i>Sansevieria</i> species	Europe, Japan
<i>F. poae</i>	Cereal	Worldwide
<i>F. polyphialidicum</i>	Sorghum grain	Australia, Italy, South Africa
<i>F. proliferatum</i>	Asparagus, corn, mango, sorghum	Worldwide
<i>F. pseudoanthophilum</i>	Corn	Southern Africa
<i>F. pseudograminearum</i>	Barley, triticale, wheat	Drier areas worldwide
<i>F. pseudonygamai</i>	Pearl millet	Africa, US
<i>F. ramigenum</i>	<i>Ficus carica</i>	US
<i>F. redolens</i>	Many hosts	Temperate regions
<i>F. sacchari</i>	Corn, sugarcane	Mexico, Philippines
<i>F. semitectum</i>	Banana	Subtropical regions
<i>F. solani</i>	Many plant species	Worldwide
<i>F. sterilihyphosum</i>	Mango	South Africa
<i>F. subglutinans</i>	Corn	Cooler corn-growing areas
<i>F. succisae</i>	<i>Succisa pratensis</i>	Europe
<i>F. thapsinum</i>	Sorghum	All sorghum-growing areas
<i>F. torulosum</i>	Several plant species	Temperate regions
<i>F. udum</i>	Pigeon pea	Southern Asia, sub-Saharan of Africa
<i>F. venenatum</i>	Several plant species	Europe
<i>F. verticillioides</i>	Corn	Worldwide

Source: The *Fusarium* Laboratory Manual [3].

Table 1. Plant pathogen *Fusarium* species, their host, and geographic distribution.

4. *Fusarium* toxins

Mycotoxins are toxic secondary metabolites produced by fungi and are capable of causing diseases in both animals and humans. Mycotoxins may produce birth defects, abortion, tremors, and cancers [27–30]. Among the major mycotoxin-producing fungi are *Aspergillus*, *Claviceps*, *Fusarium*, and *Penicillium* species [27, 28]. *Fusarium* fungi are the most widespread in cereal-growing areas of the world and produce a diversity of mycotoxin types. The most prevalent *Fusarium* toxins are zearalenone, fumonisin, moniliformin, and trichothecenes (T-2/HT-2 toxin, deoxynivalenol, diacetoxyscirpenol, nivalenol) [5, 28, 30, 31].

Zearalenone is a group of estrogenic metabolites produced by several species of *Fusarium*, the most known of which is *F. graminearum* [5, 28]. Zearalenone is the generic name for a complex macrocyclic molecule and is derived from the perfect stage of the fungus *F. graminearum* (*Gibberella zeae*) [28]. *Fusarium* infection and zearalenone production are most notable on

barley, corn, oat, sorghum, and wheat. *Fusarium* causes crown rot of corn, and scab of barley, oat, and wheat. Zearalenone is produced in infected plants in the field and in stored food and feed stuffs including cereal grains [5, 28].

Zearalenone is frequently implicated in reproductive disorders of farm animals and occasionally in hyperoestrogenic syndromes in humans [28, 32]. It has been reported that zearalenone possess estrogenic activity in cattle, pigs, and sheep. The biotransformation for zearalenone in animals involves the formation of two metabolites α -zearalenol and β -zearalenol, which are subsequently conjugated with glucuronic acid [32]. Moreover, zearalenone has also been shown to be hepatotoxic, hematotoxic, immunotoxic, and genotoxic.

Fumonisin are hydroxylated long-chain alkylamines esterified with propanetricarboxylic acid moieties produced by *Fusarium moniliforme* worldwide [33, 34]. The fumonisins have been reported carcinogenic in laboratory rats. It has also been reported that consumption of corn contaminated with *Fusarium moniliforme* is associated with higher than average incidence of esophageal cancer, and fumonisins may be responsible. Fumonisin are structurally similar to sphingosine and may exert their biological activity through their ability to block key enzymes (sphinganine- and sphingosine-N-acyltransferases) involved in sphingolipid biosynthesis.

Moniliformin is produced by several *Fusarium* species on cereals worldwide [31, 35]. Moniliformin is a small and ionic molecule that forms only a single sensitive fragment ion in the collision cell of a tandem mass spectrometer. There is great variability in the moniliformin synthesized by *Fusarium* spp. [35]. It has been reported that moniliformin in large amounts acts at the level of sugar metabolism and is cytotoxic at high concentrations in mammalian cells [35]. In addition, this toxin causes intoxication, and the lesions include intestinal hemorrhage, muscle weakness, breathing difficulty, cyanosis, coma, and death.

Trichothecenes are a very large group of mycotoxins produced by various species of *Fusarium*, *Cephalosporium*, *Myrothecium*, *Stachybotrys*, *Trichoderma*, *Trichothecium*, and *Verticimonosporium*. The generic name “trichothecene” has been derived from a *Trichothecium* species from which the first of these related compounds was isolated [28]. Trichothecenes belong to sesquiterpene compounds. They are produced on many different grains, e.g., corn, oats, and wheat by various *Fusarium* species such as *F. graminearum*, *F. poae*, and *F. sporotrichioides* [28, 36, 37].

There are several types of trichothecene mycotoxins, including deoxynivalenol, diacetoxyscirpenol, HT-2 mycotoxins, neosolaniol, nivalenol, satratoxin-H, T-2 mycotoxins, verrucarins, and vomitoxin. Exposure to trichothecene mycotoxins can cause different symptoms in people such as dry eyes, tiredness, fatigue, vomiting, diarrhea, abdominal pain, mental impairment, rash, and bleeding [28]. In addition, T-2 mycotoxins are also substances for biological warfare that can be absorbed through a person's skin [37].

Trichothecenes are typically found in plants when the autumn is cool and wet that delays harvest of grains such as corn. The toxins are also found in animal feeds that contain contaminated grain with *Fusarium*. Joffe [39] reported that trichothecenes are among the most toxic mycotoxins. He found that the LD₅₀ rate for laboratory mice given trichothecene mycotoxins is between 1 and 7 mg/kg, depending on the specific type of trichothecene and the method of exposure [38, 39]. Toxicity of trichothecene in human is documented since 1913 when people in Russia consumed cereals that overwintered in the field [38, 39].

5. Conclusions

After about 200 years from the first introduction of *Fusarium*, there is not a universal agreement on the taxonomy of *Fusarium* species yet. However, considerable efforts are underway to use the available information to develop a uniform taxonomy system for *Fusarium*. *Fusarium* species infect most of plant species and cause substantial crop and yield losses. Effective management of *Fusarium* diseases in crops is not only essential for preventing crop losses but also needed to minimize mycotoxin production in food and feed products. Major strategies for preventing/minimizing mycotoxin production should be based on preventing growth of *Fusarium* in plants and therefore mycotoxin formation, reducing or eliminating mycotoxins from contaminated food and feed stuffs, or diverting contaminated products to low risk uses.

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