Journal of Animal &Plant Sciences, 2014. Vol.21, Issue 2: 3326-3343
Publication date 30/4/2014, **http://www.m.elewa.org/JAPS**; *ISSN 2071-7024*

The Importance of *Fusarium* Fungi in Wheat Cultivation – Pathogenicity and Mycotoxins Production: A Review

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1. ABSTRACT

Globally, cereals occupy about 50% of arable land. In Poland, that share is over 70%. In the structure of cereal crops, wheat is a dominant species. It occupies an area of 2.2 million hectares. The major part of this area is winter wheat, which is responsive to infection by pathogenic fungi. In recent years, the occurrence of pathogenic fungi of the genus *Fusarium* has been increasing. Their harmful effect consists of deterioration of the quality and quantity of yield and production of mycotoxins that can pose a threat to plants, animals and humans. In order to prevent the development of fusariosis, fungicides are used. However, incompetent and intensive use of fungicides may induce the resistance in strains previously sensitive to those substances. The aim of this essay is to present the problem of pathogenic *Fusarium* species occurrence in wheat crops and to discuss methods of fungicide control and related problems.

2. INTRODUCTION

Wheat has accompanied humans as a bread cereal for many decades now. Its cultivation was known as early as the Neolithic Age, about 7000 years BC, as evidenced by archaeological discoveries in the Middle East and China. To this day, this plant does not lose its importance, and among cereals cultivated in Poland it takes first place in terms of tillage area (Szempliński 2012). Cereals occupy about 50% of arable lands in the whole world. In Poland their share is over 70%, which is about 8.3 million hectares (Jaczewska-Kalicka and Krasiński 2011). The dominant species is wheat, which occupies an area of about 2.2 million hectares. Over 80% of this area is winter wheat, and the remainder is spring wheat (Statistical Yearbook GUS 2007). Wheat has high requirements in relation to climatic and environmental conditions (Rosada *et al.* 2010). It is also very sensitive to pests, especially pathogenic fungi that cause leaf, head, and stem diseases (Jaczewska-Kalicka 2010). Stem-base diseases in cereals may be caused by several species of pathogenic fungi. In Poland the most important are two of them: eyespot and stem-base rot, caused by fungi of the genera *Tapesia* and *Fusarium*. These diseases contribute annually to a significant loss in winter wheat production (Korbas 2004). The major economic importance among fungal infections of cereals is attributed to diseases caused by *Fusarium spp.* (Narkiewicz-Jodko *et al.* 2005). Especially stem-base rot and *Fusarium* head blight (FHB) constitute a serious problem in wheat cultivation, contributing to a significant reduction in yield and deterioration of its quality. Among the most dangerous fungal pathogens of wheat head are *Fusarium culmorum, F. avenaceum* and *F. graminearum*. Other species of minor importance are *F. poae, F. oxysporum, F. sporotrichioides* and *F. verticillioides*. *Fusarium* head blight leads to a decrease in yield and reduces germination. Moreover, infested grain is often contaminated with mycotoxins. *Fusarium* epidemics can be a considerable problem for seed producers (Infantino *et al.* 2011; Xu *et al.* 2008). Other frequently occurring fungal pathogens of wheat in Poland include *Blumeria graminis* that causes powdery mildew, *Puccinia recondita*-causing brown rust of wheat, and *Phaeosphaeria nodorum*- causing glume blotch (Tratwal and Walczak 2012).

3. *FUSARIUM SPP.* – CHARACTERISTICS AND PATHOGENICITY

3.1. Description and taxonomy: The genus *Fusarium* contains over 70cosmopolitan species, occurring in natural conditions in different regions of the world. They are common in soil, as saprophytes. They can also grow on plant residues and other organic substrates. Some of them are facultative parasites, which, under conducive conditions, may cause plant diseases of both the underground and the aboveground parts (Leslie and Summerell 2006).According to the current taxonomy, *Fusarium* fungi belong to the kingdom: *Fungi*, phylum: *Ascomycota*, subphylum: *Pezizomycotina*, class: *Sordariomycetes*, subclass: *Hypocreomycetidae*, order: *Hypocreales*, family: *Nectriaceae* and genus: *Fusarium*[Index Fungorum (http://www.indexfungorum.org); Catalogue of Life (http://www.catalogueoflife.org)].The teleomorphs of *Fusarium* species are mostly classified in the genus *Gibberella*, because they share the same species as type. In nature, *Fusarium* anamorphs occur more frequently than their *Gibberella* teleomorphs (Gräfenhan *et al.* 2011; Moretti 2009).

Complete review of the main taxonomic systems that have contributed to the defining of the modern taxonomy of *Fusarium* and various methods of their identification were described in the comprehensive manual of Leslie and Summerell (2006). This excellent and the most current work contains an updated description of 70 species within the genus.

The main approach for the *Fusarium* classification is still morphology. *Fusarium* colonies are usually fast growing, pale or brightly coloured, and may have a cottony aerial mycelium. The tinge of the thallus varies from whitish to yellow, brownish, pink or reddish. *Fusarium* species can create three types of spores: macroconidia, microconidia and chlamydospores. Septated macroconidia (3-8 x11-70 µm) are colourless, fusiform to sickle-shaped, often with an elongated apical cell and pedicellate basal cell; they are produced in specialized structures called sporodochia. They can also be produced on monophialides and polyphialides in the aerial mycelium. Monophialide is a conidiophore that has only one opening or pore through which endoconidia are extruded. Polyphialide is a structure with two or more openings or pores. Macroconidia tend to accumulate in ropes or balls. The different shape of macroconidia remains the most important feature for recognition the species. Microconidia (2-4 x 4-8 µm) are produced only in the aerial mycelium. Their presence or absence is a primary feature in *Fusarium* taxonomy. Microconidia have variable shapes and sizes. Usually they are 1-celled, smooth, colourless, ovoid to cylindrical and accumulated in balls, sometimes in chains. The third type of spores is called chlamydospores. They are thick-walled, colourless and may be formed singly, in pairs, in clumps or in chains. The outer wall of chlamydospores can be smooth or rough (Nelson *et al.* 1994; Summerell *et al.* 2003, Leslie and Summerell 2006; Moretti 2009;)

3.2. *Fusarium* as a plant pathogen: *Fusarium spp.* are considered some of the most dangerous pathogens of cereals, potatoes, vegetables, *Fabaceae*, ornamental and forest plants, causing significant economic losses.

Most of them are polyphagous, infecting different plant species. They can infect plants at any stage of growth, causing seedling blight, root rot, stem-base rot, leaf fusariosis and *Fusarium* head blight in cereals and (Champeil *et al.* 2004a; Łukanowski and Sadowski 2002). In wheat cultivation, the most considerable problem are two diseases: stem-base rot and *Fusarium* head blight, also known as scab. It is extremely difficult to reduce the occurrence of those diseases, because of the large share of cereals cultivation in Poland. Another factor influencing the occurrence of diseases is weather conditions that affect both plant growth and the presence of infection (Doohan *et al.* 2003; Narkiewicz-Jodko *et al.* 2005). Fungi of the genus *Fusarium* are present with high intensity in warm and wet years, with a large amount of precipitation, because they spread through macroconidia, which are transferred to the upper plant organs in raindrops. They can also produce forms called perithecia. After the rains, these structures throw out ascospores that are transferred with the wind directly to the heads. Infection of the head and grain occurs when the temperature during the flowering exceeds 20°C and the humidity is greater than 85-90% for at least 24-40 hours (Champeil *et al.* 2004a). The research of many authors shows that the main factors of stem-base rots are *Fusarium culmorum* and *F. avenaceum*. *F. culmorum* prefers temperature above 25°C and low precipitation, while *F. avenaceum* occurs more often in cooler (10-25°C) and humid growing seasons (Pląskowska 2010). A vastly important factor is the moment when the infection reaches the plant that is the most sensitive in the flowering stage or in the initial stage of milk ripeness of grain. Under favourable conditions the infection of seed can occur. Highly infected grain is characterised by decline in the quality, reduced weight of 1000 grains, low protein content, chalky, impaired ability to germinate, deterioration in gluten quality and quantity (Gilbert 1992, Boyacioglu and Hettiarachchy 1995; Dexter *et al.* 1997;). Such grain also contains mycotoxins, which may be dangerous to human and animal health: zearalenone and deoxynivalenol (vomitoxin). These toxins from grain get into all of its milling productsand they can be found even in baked bread (Grabarkiewicz-Szczęsna *et al.* 2001). The presence of mycotoxins in infested grain depends on environmental factors and on the genotype of plant (Miedaner *et al.* 2001). A major problem in the cultivation of cereals is FHB, which contributes to significant quantitative losses and deterioration of the quality of grain and its products. Yield losses caused by *Fusarium* head blight can be very high and in extreme cases reach up to 70%. In European conditions the losses come to 10-20% (Sayler 1998). FHB is a pre-harvest disease, but *Fusarium* species can also grow post-harvest. The fungus grows if wet grain is not dried quickly and efficiently. The contagion during the flowering or at the beginning of milk ripeness of grain is called overt fusariosis. Affected wheat grains are small, light, wrinkled and sometimes covered with a pink or white down, and they have a reduced ability to germinate. Ovalor round stains with clear centres and dark edges may be visible on the back of the grain (Parry *et al.*1995; Sutton 1982). When the infection occurs in the mealy ripeness or kernel hard stage, it is called covert fusariosis. Grain is normally formed and has high germination ability (Narkiewicz-Jodko 1998; Pirgozliev *et al.* 2003). The disease results from the development of a complex of two kinds of pathogenic fungi: *Microdochium* and *Fusarium*. The*Fusarium* complex consists of five main species: *F. graminearum*, *F. culmorum*, *F.avenaceum*, *F. poae* and *F. tricinctum*, of which the most common species in Poland and Europe are *F. avenaceum, F. graminearum* and *F. culmorum* (Champeil *et al.* 2004a; Chełkowski *et al.* 2012).Individual *Fusarium* species can produce a range of mycotoxins in infected grain, whereas *Microdochium* species are considered unable to produce mycotoxins. Moreover, *Fusarium* species predominate in hotter regions of Europe, while in cooler maritime areas, *Microdochium* species are favoured (Xu *et al.* 2008). The climate is the principal factor affecting the development of *Fusarium* head blight - humidity determines the intensity of the disease, while precipitation determines inoculum levels (Francl 1998). It may also affect the production of mycotoxins in the field (Magan *et al.* 2002). The effects of climate are uncontrollable and difficult to predict due to their complexity (Champeil *et al.* 2004a).

4. MYCOTOXINS PRODUCED BY SELECTED *FUSARIUM* SPECIES

For cereal products, one of the most important elements of health risk is the possibility of mycotoxins accumulation in the kernels. These toxins are the products of fungal secondary metabolism that occurs when growth stops or slows distinctly. Mycotoxins are the major problem in food safety, they are harmful to both animals and humans (Gilbert and Tekauz 2000; Ngoko *et al.* 2008). Some of them are produced before harvest (fumonisins, zearalenone and trichothecenes), while others are produced after harvest (aflatoxins and ochratoxin A). *Fusarium* species are responsible for mycotoxins production before harvest (Champeil *et al.* 2004b). The main toxins produced by pathogenic *Fusarium* species are: zearalenone, deoxynivalenol and derivatives, nivalenol, T_2-toxin and HT_2-toxin (Placinta *et al.* 1999).They occur on a worldwide basis in cereal grains, animal feed and forages. Other important *Fusarium* toxins include moniliformin and fusaric acid. Table 1 summarises the key *Fusarium spp.*, which can be involved in head blight in cereals, and the major toxins produced by them. Contamination of feed grains is inevitable since many toxigenic *Fusarium* species are also common phytopathogens, causing cereal crop diseases, which are difficult to control (D'Mello *et al.* 1999). Excessive moisture in the field and storage, humidity, drought and temperature extremes is principal environmental factors that determine the intensity of mycotoxins contaminations (Coulombe 1993).

Table 1: Important species of*Fusarium* infecting cereals, their frequency of occurrence in Poland and Europe, and mycotoxins produced

Species	Frequency	Aggressiveness to head	Major mycotoxins produced
F. culmorum	+++++	high	deoxynivalenol (DON), 3-acetyl-deoxynivalenol (3ADON), 15- acetyl-deoxynivalenol (15ADON), nivalenol (NIV), fusarenone (FUS), zearalenone (ZEN)
F. graminearum	+++++	high	DON, 3 ADON,15ADON, NIV, FUS, ZEN
F. sporotrichioides	++	low	T_2-toxin, HT_2-toxin, neosolaniol (NEO), diacetoxyscirpenol (DAS), FUS, ZEN
F. poae	+++	average	T_2-toxin, HT_2-toxin, NIV, DAS, FUS
F. verticillioides	++++	average	fumonisins, moniliformin, fusarin C
F. proliferatum	++	average	fumonisins, moniliformin, fusarin C
F. avenaceum	++++++	average	moniliformin, beauvericin
F. cerealis	++	high	NIV, FUS, ZEA
F. tricinctum	++	low	moniliformin
F. oxysporum	++	saprophyte	moniliformin, wortmannin, fusaric acid
F. equiseti	++	saprophyte	fusarochromanone, ZEN, DAS

4.1. Trichothecenes: Trichothecenes (Fig. 1) are the largest group of fungal toxins. They are classified in the group of tricyclic sesquiterpenes and are characterised by the presence (type A trichothecenes) or absence (type B trichothecenes) of a keto group at the C-8 position. Type A corresponds to T_2-toxin, HT_2-toxin, diacetoxyscirpenol (DAS) and scirpenol. Type B trichothecenes include deoxynivalenol (DON, vomitoxin) and its derivatives: 3-acetyl-deoxynivalenol (3ADON) and nivalenol (NIV). Trichothecenes are potent inhibitors of eukaryotic protein synthesis and have gained particular notoriety as a group of materials highly toxic to both plants and animals. *Fusarium culmorum*, *Fusarium graminearum* and *Fusarium sporotrichioides*are the main producers oftrichothecenes. These toxins are common fungal contaminants of cereals and occur naturally worldwide in the cultivation of wheat and other cereals (Brown *et al.* 2001; Champeil *et al.* 2004a; Wagacha and Muthomi 2007).Apart from their phytotoxicity, trichotecenes play an important role as virulence factors in head rots of wheat and maize caused by *Fusarium graminearum* (Desjardins *et al.* 1996; Harris *et al.* 1999). Increase of mycotoxin-contaminated grains is caused by using monocultures and minimum tillage. The effect of these systems is the accumulation of fungal inoculum in soil and crop debris. The most frequently detected toxin in Europe is deoxynivalenol (Korbas and Horoszkiewicz-Janka 2007). DON retards the germination and growth of wheat, delays the growth of the grain and the coleoptiles tissues (Snijders and Perkowski 1990). In mature plants, deoxynivalenol seems to circulate in the phloem, with the concentration in plant following a descending gradient from the rachis, through the lemmas and grains to the peduncle. Moreover, from the fourth day after inoculation, the flower parts, rachis and peduncle contain larger amounts of DON below the point of infection than above it (Savard *et al.*2000; Sinha *et al.* 1997). The production of deoxynivalenol by *Fusarium* is believed to play an important role in the pathogenesis of head blight. The research shows that *Fusarium culmorum*strains belonging to the chemotype of DON are more aggressive towards barley seedlings. Furthermore, DON-producing *F. culmorum* isolates are more virulent than those producing NIVin wheat. These conclusions strengthen the contribution of DON in the pathogenicity of *F. culmorum* in different cereal cultivations (Hestbjerg *et al.* 2002; Muthomi *et al.* 2002). Deoxynivalenol can induce complete decline of chloroplast pigments at sub-lethal concentrations (Rotter *et al.* 1996). Trichothecenes are also a primary determinant of *Fusarium graminearum* pathogenicity in most wheat cultures. It is observed that a lack of trichothecenes synthesis by *F. graminearum* resulted in susceptible plants being capable of slowing down and even stopping*Fusarium* spread (Eudes *et al.* 2001). Both deoxynivalenol and nivalenol are characterised by strong toxicity to plant tissues in growth. They cause yield reduction in spikes even at low concentration. It is possible that, in the presence of the toxin, plant defence mechanisms are not induced fast enough, therefore the aggressiveness of the pathogen increases (Ittu *et al.* 1995). In contaminated plant whole spikelets prematurely senesce, and if the rachis is infected, the head above the point of infection senesces. Kernels from infected spikelets are usually shrivelled and are chalky white or pink in colour (Edwards 2004). *Fusarium* infection can result not only in yield losses but also in deterioration of milling and malting quality, and in the contamination of grains with trichothecenes, which are harmful to all organisms. Consumption of food or forage contaminated with these substances causes both animal and human diseases. In mammals, the absorption of trichothecenes causes blood and digestive disorders. Emesis is observed after the ingestion and absorption of at least 10 mg $DON \cdot kg^{-1}$, together with irritation of the mouth and oesophagus mucous membrane (Champeil *et al.* 2004a; Edwards 2004). The adverse effects of individual trichothecenes in porcine and non-porcine livestock are summarised in Table 2.

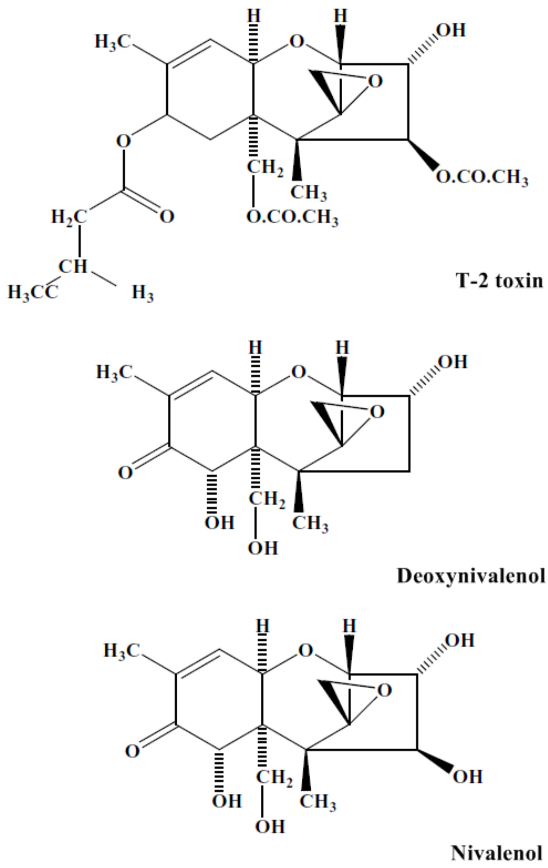

Fig. 1: Chemical structure of trichothecenes produced by *Fusarium*

In humans, the absorption of trichothecenes leads to burning sensations in the mouth and stomach, headaches, a reduction in red blood cell count, bleeding, necrosis of throat and stomach. In some cases, trichothecenes poisoning may even lead to death (Champeil *et al.* 2004a).

4.2. Fumonisins: Fumonisins are long-chain amino polyalcohols. They consist of a 20-carbon aliphatic chain with two ester linked hydrophilic flank chains. This structure is similar to sphingosine, an essential phospholipid within cell membranes. Although fumonisins have a relatively simple chemical structure, they may have diverse and complex effects in animals and human systems. The toxicity of fumonisins is a result of competition with sphingosine in sphingolipids metabolism (Desjardins and Proctor 2007; Riley *et al.* 1996). The most significant food source contaminated by these mycotoxins is maize, but the presence of fumonisins was also found in wheat grain. A large number of commodities in the world have been analysed for fumonisins contamination, however they have mostly been reported in maize and its products (De Girolamo *et al.* 2011; Scott 2012). Few studies (Busman *et al.* 2012; Palacio *et al.* 2011) have been carried out on the natural contamination of wheat with fumonisins. Although, *Fusarium verticillioides* isolated from wheat has been reported to produce high concentrations of these toxins (Mashinini and Dutton 2006; Stanković *et al.*2012).

The most toxic representative of these group is fumonisin B_1 (Fig. 2) which is produced mainly by *Fusarium proliferatum* and *F.verticillioides,* commonly occurring in cereal crops(Edwards *et al.*2002; Pławińska-Czarnak and Zarzyńska 2010).Fumonisin B_1 is known to induce toxicity on contact in various plant tissues.

Table 2: Adverse effects of individual trichothecenes in livestock

Animal species/type	Trichothecene	Effects
Pigs	DON	emesis; reduced feed intake; decreased growth; stomach lesions; reduced blood levels of total protein, albumin, Ca and P; temporary decrease in serum protein levels; renal lesions
	NIV	profound reduction in feed intake; increased time to consume feed
	T_2-toxin	dermatitis of nose, snout and buccal commissures; reduced growth; decreased blood glucose levels; increased blood levels of inorganic P and Mg; decreased red blood cell amount; reduced corpuscular volume and haemoglobin concentration; reduced leukocyte count; decreased antibody formation
Broiler chickens	DON	increased weight of heart, gizzard and bursa of Fabricius
	NIV	gizzard erosions; reduced weight of liver
	T_2-toxin	decreased bodyweight gain; oral lesions
	DAS	decreased bodyweight gain; mouth lesions
Turkey poults	T_2-toxin	reduced weight gain; oral lesions
	DAS	reduced feed intake and weight gain; oral lesions
Geese	T_2-toxin	decreased egg yield and hatchability; inhibition of follicle maturation in ovaries; follicle degeneration; lesions in adrenal and thyroid glands
Cattle	DAS	anorexia; gastro-intestinal lesions; diarrhoea; reduced milk production

Disruption of sphingolipid metabolism, resulting in accumulation of sphingolipid bases, has been implicated in the development of disease symptoms, which include changes in the plasma membrane, disruption of the electrolyte leakage, chloroplast degeneration, chlorosis and necrosis (Abbas *et al.* 1993; Lynch *et al.* 2004).

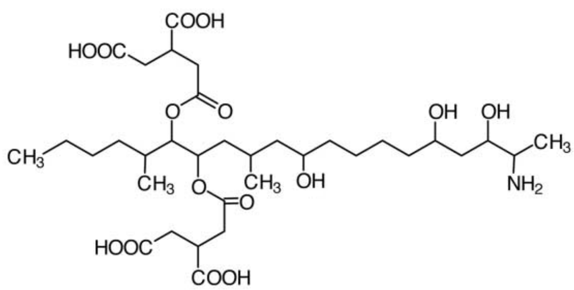

Fig. 2 Chemical structure of fumonisin B_1

The fumonisins were the most recent group of fungal toxins identified after they were found to be a causative factor of the fatal syndrome, equine leukoencephalomalacia. They have since been shown to have a number of deleterious effects in animals and humans (Kellerman *et al.* 1990, Edwards *et al.* 2001;). Fumonisins induce disorders after consumption of contaminated feed or food (Reddy *et al.* 2010).The diseases include porcine pulmonary edema, hydrothorax in pigs, hepatocarcinoma in rats, and immunosuppression in poultry. Absorption of fumonisins causes the formation of cancerous tumors in laboratory rodents and there is an epidemiological correlation between the consumption of infected grain and human oesophageal cancer in some regions of the world (Rheeder *et al.* 1992, Bucci and Howard 1996, Proctor *et al.* 2002;).

4.3. Zearalenone: Zearalenone (ZEN) (Fig. 3) is a non-steroidal estrogenic mycotoxin produced mainly by *Fusarium culmorum*, *F. graminearum* and *F. sporotrichioides*. This toxin is most frequently isolated from maize; but it also contaminates other cereals, including wheat, barley, oat and sorghum. It is associated with head rot and stalks rot in maize and with scab in wheat, moreover it is a natural contaminant of hay (Coulombe 1991; Krska *et al.* 2003). ZEN is one of the most common mycotoxins produced by *Fusarium* in the temperate regions of Europe, Asia and America (Mankevičienė *et al.* 2011). It belongs to a very large family of fungal metabolites derived by cyclisations and modifications of non-ketide precursors. ZEN has a chemical structure similar to estrogen, and it can produce an estrogenic response in animals. It has also a close structural similarity to antibiotic metabolites produced by many species of fungi (Desjardins and Proctor 2007). It is established that zearalenone is characterised by a relatively low toxicity, with an LD_{50} value of 2-10 $g \cdot kg^{-1}$ body weight as determined with mice (Flannigan 1991). However, its role as an endocrine disrupter is being recognised in detailed research, with effects in males and females of different species of mammals (Pfohl-Leszkowicz *et al.* 1995).It was discovered to be the cause of reproductive disorders in domestic animals. *Fusarium* fungi are able to producing both *trans* (α-zearalenol) and *cis* (β-zearalenol) forms of ZEN on grain. These metabolites bind to estrogen receptors to varying extents, causing hyperestrogenism resulting in various reproductive and infertility problems, especially in pigs. Those animals are particularly susceptible to this compound because their estrogen receptors have a high affinity for α-zearalenol, which is three to four times more estrogenic than ZEN (Fitzpatrick *et al.* 1989; D'Mello *et al.* 1999; Moss 2002). Swine diseases caused by zearalenone include enlargement and swelling of the vulva in sows and gilts (vulvovaginitis), swelling of the mammary glands, atrophy of the ovaries, vaginal and rectal prolapsed. In boars ZEN reduces libido and causes a reduction in sperm quality, while in young males it may cause swelling of the prepuce, testicular atrophy and enlargement of the mammary glands (Prelusky *et al.* 1994).ZEN and its derivatives are capable of inhibiting mitogen-stimulated lymphocyte proliferation and can cause thymic atrophy and macrophage activation (Visconti *et al.* 1991). Zearalenone can be an important etiologic agent of intoxication in young children and foetuses exposed to this compound, which causes premature thelarche and breast enlargement (Mankevičienė *et al.* 2011). ZEN may also be one of the risk factors that influence the occurrence of mammary gland cancer in women (Kuciel-Lisieska *et al.* 2008). Although in west European countries ZEN in considered as a toxin, a number of studies have shown that it may also have a positive effect on plant growth. It was investigated as a regulator of the flowering process (Biesaga-Kościelniak and Filek 2010). It is established that exogenous application of ZEN in the culture of winter wheat isolated embryos strongly increases the percentage of generative plants. Research indicated that zearalenone also shows similar activity to plant hormones in some physiological processes (Biesaga-Kościelniak 2001). The application of ZEN may be useful in *in vitro* cultures. The studies have shown that ZEN stimulates the regeneration processes, growth of the callus tissue and its differentiation in wheat (Biesaga-Kościelniak *et al.* 2010). In view of its hormonal activity there is much information about zearalenone in the literature on growth hormones, used in animal production. Some countries, such as the USA, permit the use of zearalenone for increasing meat production. Because any compound with hormonal activity may be carcinogenic or genotoxic and there is some information that zearalenone may show both types of activity in some animal species, this practice is banned in the countries of the European Community (Moss 2002).

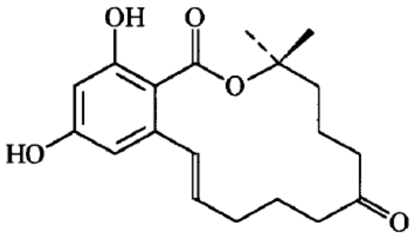

Fig. 3: Chemical structure of zearalenone

4.4. Masked mycotoxins: Recently glycosylated derivatives of deoxynivalenol and zearalenone called 'masked mycotoxins' were identified in wheat grain. These toxins are result of the glycosylation process in wheat tissues in the second phase of plant metabolism. Conjugation with glucose can convert DON into DON-3 glucoside (DON-3G) and ZEN into ZEN-14 glucoside (ZEN-14G). Chemically altered mycotoxins, as they escape analytical detection designed to DON and ZEN, because of changed polarities and masses (Vendl *et al.* 2009).They are recognized as potentially hazardous for animal and human because they can be transformed to DON and ZEN in the digestive tract (Chełkowski *et al.* 2012; Stępień and Chełkowski 2010).Occurrence of DON-3G has been proven in wheat kernels (Berthiller *et al.* 2009). It was also found in malt and beer (Lancova *et al.* 2008). Schneweis *et al.* (2002) proved ZEN-14G occurrence in wheat samples originating from Bavaria. There is a little information on the occurrence of this ZEN derivative in wheat and other cereal grains in Poland (Perkowski *et al.* 1997, Gromadzka *et al.* 2008;).

Table 3: Maximum permissible level of mycotoxins content

Mycotoxin	Product	Maximum permissible level ($\mu g \cdot kg^{-1}$)
Deoxynivalenol	unprocessed cereals	1 250
	unprocessed durum wheat, oat	1 750
	unprocessed corn	1 750
	cereals intended for direct human consumption, cereal flour, bran	750
	pasta	750
	bread (include bakery products), confectionery products, biscuits, cereals	500
	processed cereal-based food, food for infants and young children, baby products	200
Zearalenone	unprocessed cereals	100
	unprocessed corn	350
	cereals intended for direct human consumption, cereal flour, bran	75
	refined corn oil	400
	bread, confectionery, biscuits, cereals	50
	processed cereal-based food , food for infants and young children, baby products	20
	corn intended for direct human consumption, corn snacks, corn flakes	100
	processed corn-based food for infants and young children,	20
Fumonisins	unprocessed corn	4 000
	corn intended for direct human consumption	1 000
	corn snacks, corn flakes	800
	processed corn-based food for infants and young children,	200

4.5. Mycotoxins content limits: Cereal products may be contaminated by mycotoxins at any stage, from the growth of the plant, through the harvest, as well as during processing, storage and transport of the end product. The maximum permissible level of contamination by selected mycotoxins (Tab. 3) is regulated by Commission Regulation (EC) No. 466/2001 of8th March 2001 as amended (Commission Regulation(EC) No. 466/2001of 8th March 2001; Commission Regulation (EC) No. 856/2005 of 6th June 2005;Commission Regulation (EC) No. 1126/2007 of 28th September 2007).

5. FUNGICIDE CONTROL OF *FUSARIUM* HEAD BLIGHT

In recent years the occurrence of fungal infections of cereals has been increasing everywhere, which may be explained by changing climatic conditions (Ioos *et al.* 2005). This indicates a need to intensify protective measures. Wheat is in particular one of the crops most prone to *Fusarium* infections and critical mycotoxin problems. Over the last decade the quality and the safety of grain productions have increased in importance. Management of *Fusarium* head blight includes many effective protection procedures, especially based on agrotechnical, biological and immunological methods of controlling infections, as well as fungicide application (Blandino *et al.* 2006; Grishechkina *et al.*2012).Unfortunately, there is currently no single effective method of reducing the incidence of FHB or mycotoxin contaminationin cereals. Fungicide application is one measure available to reduce the risk; however, it does not guarantee getting rid of the pathogen(Horsley *et al.* 2006, Baturo-Cieśniewska *et al.* 2011;). The efficacy of fungicide use for the control of FHB and mycotoxins production varies from being highly effective to even increasing mycotoxin levels (Müllenborn *et al.* 2008). Some of the reasons of the variable effects of fungicides on FHB are probably cultivar resistance, fungicide efficacy, fungicide coverage, timing and frequency of applications, different epidemiology and the natural variation in aggressiveness of individual pathogens (Homdork*et al.* 2000; Mesterhàzy *et al.* 2003). Application at flowering stage seems to be the best time for the reduction of *Fusarium* infection risk (Chala *et al.* 2003).

5.1. Efficacy of various types of fungicides : Fungicide applications, pre-harvest are necessary whether in intensive or sustainable cereal production systems. Thus *Fusarium* species colonising cereals will be exposed to various groups of fungicides, such as imidazoles, benzimidazoles, triazoles, morpholines or strobilurins (Mateo *et al.* 2011). Each group is characterised by a different mechanism of action and different efficacy in prevention of *Fusarium* diseases. In the European Union, many triazoles are registered for wheat. As shown in various studies, they proved to be the most active compounds against the present set of toxigenic fungal species (Matthies and Buchenauer 2000; Menniti *et al.* 2003). Fungicides of this type have an influence on fungal metabolism, mainly by inhibition of ergosterol biosynthesis. They often cause striking morphological deformations, irregular cell wall thickening and excessive branching of fungi. They lead to the inhibition of spore germination, initial cell growth and dry weight increase (Ramirez *et al.* 2004).The most widely used triazole fungicides against FHB are tebuconazole and metconazole. They show high efficiency against *Fusarium culmorum* and other fungal pathogens of wheat (Simpson *et al.* 2001, Ioos *et al.* 2005;). In studies by Sikora and Banachowska (2006), a group of 8 fungicides was investigated for their activity against *Fusarium culmorum*. Among all tested active compounds, metconazole proved to be the most effective. In many studies, triazole fungicides: tebuconazole and metconazole were shown to be effective in reducing both FHB and DON production (Jennings *et al.* 2000, Edwards *et al.* 2001;). Pirgozliev *et al.* (2002) showed a great reduction in FHB and DON in grain treated with metconazole, which indicates that this fungicide is very effective against both *Fusarium culmorum* and *F. graminearum*. Dardis and Walsh (2000) also reported that this compound was the most effective of a range of fungicides tested against *F. culmorum*. Several studies on chemical control of FHB and other *Fusarium* infections in grains report that the best results in artificially inoculated trials are obtained after the application of tebuconazole (Henriksen and Elen 2005; Mesterhàzy *et al.* 2003). According to Cromey *et al.* (2001), tebuconazole considerably reduces FHB incidence as well as *Fusarium* and mycotoxins levels in grain. Another triazole fungicide, prothioconazole, was highly effective in reducing the mycelial growth of

Fusarium avenaceum, *F. culmorum, F. graminearum, F. poae, F. sporotrichioides*and *F. tricinctum*. There was evidence that application of fungicides at flowering was more efficacious than in the other stages of growth (Müllenborn *et al.* 2008). Prochloraz is an imidazole derivate and its mechanism of action is similar to that of triazole fungicides. Like tebuconazole, it is extensively applied in agriculture to control fungal growth in cereals in many European countries (Ramirez *et al.* 2004, Mateo *et al.* 2011;). According to Menniti *et al.* (2003), its application in the field reduces the production of deoxynivalenol by an average of 43%. Prochloraz is effective especially against *Fusarium graminearum, F. avenaceum* and *F. culmorum* when infection pressure is low to medium. This compound inhibits mycelial growth of pathogen and reduces 3AcDON production (Matthies *et al.* 1999; Pirgozliev *et al.* 2003). Fungicides such as carbendazim, benomyl or thiabendazole belong to benzimidazoles group. They are specific inhibitors of microtubule assembly that act by binding to their heterodimeric subunit, the tubulin molecule. Consequently, mitotic division of the nucleus is blocked and the fungal cell loses its ability of proliferation (Davidse 1986, Cromey *et al.* 2001). The wide application of benzimidazoles in agriculture can lead to the development of resistance in pathogenic fungi (Steffens *et al.* 1996).In studies by Jones (2000), carbendazim was not as immediately effective as tebuconazole, but showed arelatively good duration of FHB control, benomyl showed levels of control equal to tebuconazole. According to Cromey (2001), carbendazim considerably reduces *Fusarium* disease incidence as well as mycotoxins content in grain. The moment of application has a major impact on its effectiveness. Hutcheon and Jordan (1990) reported that carbendazim was effective against *Fusarium avenaceum*, *F. culmorum* and *F. graminearum* by reducing their levels by about 70% in the wheat heads over the control treatment. Strobilurins, such as azoxystrobin and kresoxim-methyl, are a relatively new group of fungicides. These compounds act by blocking electron transport in the mitochondrial respiratory chain in fungi. This reduces the aerobic energy production, thereby inhibiting growth of the fungus. This new mode of action makes strobilurins an important addition to the existing fungicide range (Ypema and Gold 1999, Ramirez *et al.* 2004;).Different authors (Bertelsen *et al.* 1999; Simpson *et al.* 2001) reported that the application of strobilurins, unlike the triazoles, has little effect on the reduction of *Fusarium culmorum, F. graminearum* and *F. avenaceum*, while it is highly effective in the reduction of *Microdochium nivale.* Lienemann *et al.* (2002) and Mesterhàzy *et al.* (2003) reported that strobilurin fungicides increase DON production, although they can partially control FHB. Contrary to these researchers, Siranidou and Buchenauer (2001) observed no effect of strobilurins on DON content, or even a decrease. In studies by Nakajima (2010), azoxystrobin was not as effective as triazole fungicides, but its efficacy was about 40%. Moreover, this compound increased the DON level significantly. As suggested by Cromey *et al.* (2001), early control of FHB by azoxystrobin did not translate into lower levels of *Fusarium*or mycotoxins in grain, it only slowed the development of FHB symptoms. The new strobilurin, fluoxastrobin, seems to be more effective in controlling mycelial growth of *Fusarium* species than azoxystrobin (Ioos *et al.* 2005).

5.2. Fungicide resistance phenomenon: A major role in suppressing crops infection is played by fungicidal treatment at optimal time. The efficacy of widely used fungicides is not higher than 40-60%, and sometimes it reaches 70%. Moreover, long use of some fungicides leads to the accumulation of *Fusarium* fungi in fungal community of cereals (Grishechkina *et al.* 2012). The effectiveness of fungicides is highly variable, even within the same group. One possible cause of these different reactions is the existence of fungicide-resistant strains within the *Fusarium* species (D'Mello *et al.* 2000).A fungal population may be resistant towards a certain fungicide from the very beginning, which is termed natural resistance (Brent and Hollomon 2007). It can also become resistant towards the fungicide during the course of its use, and this phenomenon is referred to as acquired resistance (Dubos *et al.* 2011). Most of systemic fungicides have a site-specific mode of action, therefore even a small biochemical change in the fungus may lead to the development of resistance. Resistant strains arise by the selection of individual specimens or as a result of single mutations. The newly created strains may be able to avoid a block in metabolism and circumvent the action of the fungicide (Isaac 1999). Fungal resistance towards benzimidazole fungicides could be correlated with changes in benzimidazoles binding to tubulin (Steffens *et al.* 1996). Resistance towards strobilurins is caused by mutations in the cytochrome *b* gene. When glycine at position 143 is replaced by alanine, the fungus becomes highly resistant to these fungicides (Kaneko and Ishii 2009; Torriani *et al.* 2009).Intensive use of fungicides leads to the development of resistance by exerting a high selection pressure on the pathogen. Therefore it is important to apply fungicides only when they are necessary.

6. CONCLUSIONS

Fusarium species produce an extraordinary diversity of biologically active secondary metabolites, some of which are harmful to animals and humans, like mycotoxins. *Fusarium* diseases of wheat and other cereals cause significant losses worldwide, and therefore are the most important factor in quality and economy sector. The reduction of diseases and mycotoxin content in wheat is possible through the use of specific fungicides, however that does not guarantee complete elimination of the pathogen. Some of the fungicides even increase mycotoxins level. Furthermore, pathogen populations may be resistant towards certain fungicides. Because of the economic importance of *Fusarium* infections and difficulty in FHB prevention, it is necessary to acquire profound understanding of the action mode of both the pathogens and the protective measures. This issue requires further study on the use of innovative methods of control. From the perspective of modern agriculture, the ultimate goal of research on *Fusarium*, using molecular methods, is to reduce mycotoxins level in cereal grains and also to use engineering of crop plants for resistance to *Fusarium* infections and mycotoxins contamination.

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