Mycotoxigenic *Fusarium* species from agricultural crops in Malaysia

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Abstract

Phytopathogenic and mycotoxigenic *Fusarium* spp. are widespread in Malaysia. Common mycotoxigenic as well as phytopathogenic *Fusarium* spp. are *F. oxysporum* and several species members of the *F. fujikuroi* species complex, particularly *F. proliferatum* and *F. fujikuroi*. Mycotoxigenic *Fusarium* spp. infect crops in the field and can contaminate the crops after harvest and during storage. In vitro studies indicate that many isolates of mycotoxigenic *Fusarium* spp. can produce mycotoxins, suggesting that these isolates can also produce mycotoxins in the host plant. Thus, there are opportunities for mycotoxin carryover to food and feed products. Although most *Fusarium* mycotoxins are heat stable, food processing such as sorting, trimming, cleaning, milling, cooking, baking, frying, roasting, and extrusion cooking have been reported to reduce concentrations of mycotoxins in food and feed products to varying degrees. In Malaysia, more studies on human exposure to *Fusarium* mycotoxins and to other mycotoxins are needed because such data are useful for estimation of the exposure levels.

Introduction

Many species in the genus *Fusarium* are important phytopathogens worldwide. Two species, *F. graminearum* and *F. oxysporum*, are among the top 10 fungal pathogens studied by molecular biologists; this situation indicates the importance of this fungal genus as a phytopathogen.

*Fusarium* spp. are ubiquitous and cause a wide range of diseases including wilt, root rot, stem rot, fruit rot, blight, and cankers in diverse crops such as industrial crops, fruit crops, legumes, and ornamentals. The wide distribution of *Fusarium* spp. is mainly attributed to the ability of these fungi to grow on a wide range of substrates, and many species are soil-borne as well as seed-borne.

A number of *Fusarium* spp. are mycotoxin producers, and the mycotoxins are produced naturally by mycotoxigenic strains in the field or during storage. Several types of mycotoxins are produced by mycotoxigenic strains of *Fusarium* spp. including beauvericins (BEAs), deoxynivalenol (DON), fumonisins (FUMs), fusaric acids, fusaproliferin, gibberellic acid, moniliformin (MON), T-2 toxin, and zearalenones (ZEAs). Other mycotoxins produced are butenolid, chlamydosporol, enniatins, fusarins, naphthoquinones, sambutoxin, and wortmannin. Among the mycotoxins produced by mycotoxigenic *Fusarium* spp., FUMs, DON, T-2 toxin, and ZEA have received much attention due to contamination of food and feed by these mycotoxins; this state of affairs in turn can have adverse health effects on humans and animals.

Several mycotoxigenic *Fusarium* spp. and the mycotoxins produced are presented in Table 1. Among these mycotoxigenic *Fusarium* spp., several species are common phytopathogens in Malaysia including *F. fujikuroi*, *F. oxysporum*, *F. proliferatum*, *F. semitectum*, *F. solani*, and *F. verticillioides*.

Several factors have been reported to influence the production of mycotoxins. Among the factors are duration of fungal growth and colonization of the plant host, host and substrate composition, temperature, water activity, and moisture content. Higher temperature at night has been suggested to be the main factor that supports mycotoxigenic fungal growth and mycotoxin production because during night time, the plant host offers lower resistance to fungal colonization owing to a lack of energy sources. Other factors that might play a role in mycotoxin production are stress factors including water shortage and insect pest infestation. According to Atanda et al., hot and humid conditions are the two most critical factors that...
support fungal growth and development and mycotoxin production. Therefore, there are several interacting factors involved in promotion of the mycotoxigenic fungal growth and mycotoxin production. The latter also depends on the species of the mycotoxigenic fungi because different species have their own requirements for optimal growth and mycotoxin production. Mycotoxin production by mycotoxin-producing _Fusarium_ spp. may lead to contamination of agricultural crops and the related products.

Mycotoxin contamination of agricultural crops by mycotoxigenic _Fusarium_ may occur in direct and indirect ways. Many mycotoxigenic _Fusarium_ spp. are field fungi, which infect crops in the field naturally or directly contaminate them. These fungi are the initial phytopathogen infecting the crops, then develop on the crops, and when the conditions are suitable, may produce a mycotoxin. Many mycotoxigenic _Fusarium_ spp. are also phytopathogenic fungi and are able to infect a plant host. During storage of agricultural products, mycotoxigenic fungi grow saprophytically on the stored products, and mycotoxin might be produced indirectly when the environmental conditions are conducive. Therefore, agricultural products are prone to contamination with _Fusarium_ mycotoxins because contamination starts in the field at a certain stage of their growth. Most of major _Fusarium_ mycotoxins can remain in the product because these metabolites are quite resistant to many food- and feed-processing methods. This way, mycotoxins enter the food chain. Agricultural products are then consumed by humans and animals, and this way, a mycotoxin can enter the food chain.

Consumption of contaminated agricultural products or the resulting food and feed may cause mycotoxicosis, which can have several effects including teratogenic, carcinogenic, neurotoxic, estrogenic, or immunosuppressive. Contaminated products may contain multiple mycotoxins resulting in more severe effects due to synergistic actions of the mycotoxins.

### Mycotoxigenic _Fusarium_ spp. associated with agricultural crops in Malaysia

Comprehensive studies on _Fusarium_ in Malaysia started in the 1980s. From 1981 to 1986, Salleh and Strange conducted a study on the occurrence of _Fusarium_ species on diseased plants and seeds in Malaysia. They isolated 1000 isolates from rice, potato, water melon, and chili and identified the isolates as _F. avenaceum_, _F. culmorum_, _F. chlamydosporum_ etc. In a study on _Fusarium_ spp. in Malaysia, have been increasing in number. In a study on _Fusarium_ spp. associated with

### Table 1  Several species of mycotoxigenic _Fusarium_ and the mycotoxins produced worldwide

| Species               | Mycotoxins produced                                      |
|-----------------------|----------------------------------------------------------|
| _F. avenaceum_        | beauvericin, fusarin A, moniliformin                      |
| _F. culmorum_         | deoxynivalenol, 15-acetyldoxyvalenol, fusarenone, nivalenol, 3-acetyldoxyvalenol, zearalenone |
| _F. chlamydosporum_   | acuminatopyrone, chlamysporol, moniliformin, steroids    |
| _F. fujikuroi_        | beauvericin, fumonisins, fusaric acid, gibberellins, moniliformin |
| _F. equiseti_         | beauvericin, diacetoxyscirpenol, fusarochromanone, moniliformin, zearalenone |
| _F. graminearum_      | deoxynivalenol, 3-acetyldoxyvalenol, 15-acetyldoxyvalenol, fusarenone, nivalenol, zearalenone |
| _F. pseudograminearum_| deoxynivalenol, 3-acetyldoxyvalenol, zearalenone         |
| _F. oxysporum_        | beauvericin, enniatins, fumonisins, fusaric acid, isoverrucarol, moniliformin, naphthoquinone pigments, sambutoxin, wortmannin |
| _F. poae_             | diacetoxyscirpenol, fusarin C, fusarenone, HT2-toxin, nivalenol, T2-toxin |
| _F. proliferatum_     | beauvericin, enniatins, fusarin A, fusarins, fusaproliferin, moniliformin |
| _F. sacchari_         | beauvericin, fusaric acid, moniliformin                   |
| _F. semitectum_       | apicidins, beauvericin, equisetin, fusapyrone, moniliformin, sambutoxin, trichotheecenes, zearalenone |
| _F. solani_           | fusalanipyrone, fusaric acid, moniliformin               |
| _F. sporotrichioides_ | beauvericin, diacetoxyscirpenol, enniatins, fusarins, fusarenone, T2-toxin, HT2-toxin, moniliformin, neosolaniol, zearalenone |
| _F. verticillioides_  | fumonisins, moniliformin, fusarin C, fusaric acid        |

According to Desjardins, Leslie and Summerell, Kotowicz et al.
subglutinans but only sugar cane plants. Among the species recovered, according to limited data, F. sacchari can also produce mycotoxins\(^1\) (Table 1).

**Vegetable fruits**

*Fusarium* species occur on several types of vegetable fruits, some of which are consumed raw. Six species have been identified: *F. semitectum*, *F. oxysporum*, *F. subglutinans*, *F. proliferatum*, *F. solani*, and *F. equiseti*. Among the six species, *F. equiseti*, *F. semitectum*, *F. oxysporum*, *F. proliferatum*, and *F. solani* are known to produce mycotoxins\(^3\). The results revealed that there is a risk of the presence of mycotoxins on these vegetable fruits.

**Corn**

Mycotoxin-producing *Fusarium* species are common in corn because several species of *Fusarium* are associated with corn ear rot. *F. verticillioides* is the main species causing *Fusarium* ear rot, followed by *F. proliferatum* and *F. subglutinans*, but only *F. verticillioides* and *F. proliferatum* produce FUMs\(^2\) Darnetty et al.\(^25\) isolated *F. proliferatum*, *F. oxysporum*, *F. nygamai*, *F. semitectum*, *F. solani*, and *F. verticillioides* from corn samples grown in four states in Malaysia: Pulau Pinang, Perlis, Sabah, and Sarawak. In a study by Nur Ain Izzati et al.\(^26\), eight *Fusarium* species including mycotoxin-producing species were found on cultivated corn in Malaysia. The species were morphologically identified as *F. equiseti*, *F. longipes*, *F. nygamai*, *F. oxysporum*, *F. pseudograminearum*, *F. proliferatum*, *F. semitectum*, *F. solani*, *F. subglutinans*, and *F. verticillioides*. The studies by Darnetty et al.\(^25\) and Nur Ain Izzati et al.\(^26\) indicate that there is a risk of mycotoxin contamination of corn cultivated in Malaysia, particularly with FUMs, because several FUM-producing species in the *F. fujikuroi* species complex have been detected there.

FUM-producing *Fusarium* spp. are widespread in the agricultural ecosystem and therefore can infect a wide variety of crop plants\(^2\). Among the FUMs, fumonisin B1 (FB\(_1\)) is the most prevalent and is a natural contaminant of corn. The production of FB\(_1\) is commonly associated with *F. proliferatum* and *F. verticillioides*, but other species including *F. anthophilum*, *F. dlamini*, *F. fujikuroi*, *F. oxysporum*, *F. napiforme*, and many others have been reported as FB\(_1\) producers\(^2\),\(^27\). In Malaysia, five *Fusarium* species associated with plant diseases, *F. andiyazi*, *F. fujikuroi*, *F. oxysporum*, *F. proliferatum*, and *F. verticillioides*, have been isolated from various plants, namely, asparagus, ginger, oil palm, mango, banana, corn, and rice, and the ability to produce FB\(_1\) has been evaluated\(^28\). The study showed that the presence of the FUM1 gene is not associated with FB\(_1\) production because not all isolates that have the gene produce FB\(_1\). In the mycotoxin production analysis, 63 isolates comprising *F. proliferatum* (40 isolates), *F. verticillioides* (10 isolates), *F. oxysporum* (10 isolates), and *F. fujikuroi* (three isolates) were found to produce FB\(_1\) at concentrations from 0.6 to 29.2 µg/g, which correspond to low FB\(_1\) producers, suggesting that the risk of FB\(_1\) contamination is low in this case.

**Rice**

Mycotoxin-producing *Fusarium* species, particularly species within the *F. fujikuroi* species complex, are commonly isolated from bakanae-infected rice plants. In Malaysia, five species morphologically identified as *F. fujikuroi*, *F. proliferatum*, *F. sacchari*, *F. subglutinans*, and *F. verticillioides* have been isolated from bakanae-infected rice\(^29\). Only *F. fujikuroi* isolates were found to be pathogenic, i.e., causing bakanae disease and able to produce gibberellic acid (GA\(_3\)), which causes rice plants to grow abnormally tall. The study indicated that the other four *Fusarium* species may be saprophytes on rice plants although they were isolated from diseased plants.

**Mango**

Nik Mohd Izham et al.\(^30\) reported that three species of the *F. fujikuroi* species complex are associated with mango malformation in Malaysia. The species were identified as *F. proliferatum*, *F. mangiferae*, and *F. subglutinans*, with *F. proliferatum* being the most common species isolated. *F. proliferatum* is the main producer of FUMs, and under suitable conditions, there is a possibility that *F. proliferatum* associated with mango malformation can produce FUMs. A few studies have shown that *F. subglutinans* does not produce detectable amounts of FUMs\(^27\),\(^31\). So far, there are no reports of mycotoxin production by *F. mangiferae*\(^3\).

**Pineapple**

Several mycotoxin-producing *Fusarium* spp. in the *F. fujikuroi* species complex have been found to be associated with diseases of pineapple (*Ananas comosus*) fruits and leaves in Peninsular Malaysia. These species were identified as *F. fujikuroi*, *F. proliferatum*, *F. verticillioides*, and *F. sacchari*. Among these species, *F. proliferatum* is most frequently recovered from diseased pineapple\(^32\). Selected isolates of *F. proliferatum*, *F. fujikuroi*, and *F. verticillioides* from diseased pineapples can produce FB\(_1\) at variable concentrations, ranging from low to high. BEA is produced by a few isolates of *F. proliferatum*, *F. fujikuroi*, and *F. verticillioides*. In addition to FB\(_1\) and BEA, MON is produced by a few isolates of *F. proliferatum*, *F. fujikuroi*, *F. verticillioides*, and *F. subglutinans*.\(^2\)
and *F. sacchari* [32]. The rate of incidence of mycotoxin-producing *Fusarium* spp. in pineapple fruits may pose a risk to human health because of accumulation of these mycotoxins [6, 33]. In addition, there is a potential for co-occurrence of *Fusarium* mycotoxins in pineapple; this combination can have possible harmful effects [34].

**Red-fleshed dragon fruit**

Two species of the *F. fujikuroi* species complex, *F. proliferatum* and *F. fujikuroi* have been found to be the causal pathogens of stem rot disease of red-fleshed dragon fruit (Hylocereus polyrhizus) [35, 36]. Selected isolates of *F. proliferatum* and *F. fujikuroi* have been tested for FB₁, BEA, and MON production, and all the tested isolates have been found to have the ability to produce the three mycotoxins. The tested isolates of *F. proliferatum* and *F. fujikuroi* produce variable levels of FB₁ (11.97–236.80 µg/g), BEA (0.88–37.05 µg/g), and MON (0.28–70.02 µg/g). A study on mycotoxin-producing *F. proliferatum* and *F. fujikuroi* from stem rot of *H. polyrhizus* indicates co-occurrence of BEA, FB₁, and MON, which can affect the amount of mycotoxins being produced and the toxicity of the contaminated substrates [36].

**Non-agricultural crops**

*Fusarium* spp. from nonagricultural crops have been found to produce mycotoxins. Several mycotoxins including MON, FB₁, ZEA, and BEA have been detected in *Fusarium* spp. isolated from wild grasses in Peninsular Malaysia. MON was detected in *F. oxysporum*, *F. chlamydosporum*, *F. solani*, *F. proliferatum*, *F. subglutinans*, *F. sacchari*, and isolates within the *F. incarnatum-equiseti* species complex [37]. FB₁ was detected only in *F. proliferatum*, and ZEA in *F. semitectum* and *F. equiseti*. Substantial concentrations of BEA (19.5–567 µg/g) were detected in *F. semitectum*, *F. equiseti*, *F. oxysporum*, and *F. proliferatum*. Nor Azliza et al. [37] reported that *F. subglutinans*, *F. solani*, *F. compactum*, and *F. chlamydosporum* produce BEA in corn grit cultures. *Fusarium* species from grasses are regarded as endophytes because they have been isolated from apparently healthy grass tissues. Nevertheless, there is a possibility that mycotoxin-producing *Fusarium* species pose a health risk to ruminants that feed on the grasses.

**Identification of *Fusarium* spp.**

Earlier studies on *Fusarium* spp. identification have been commonly focused on microscopic and macroscopic characteristics. Although there are species that can be identified by morphological characteristics alone, many species require molecular data as well sexual cross-fertility information [39]. Identification by morphological characteristics, especially of species within the *F. fujikuroi* species complex, without molecular data and sexual cross-fertility analysis may be unreliable because microscopic and macroscopic characteristics of many species in this species complex are similar, thus leading to misidentification. In a study by Heng et al. [38] on *Fusarium* isolates from rice, sugar cane, and maize, five species were identified as *F. sacchari*, *F. fujikuroi*, *F. proliferatum*, *F. andiyazi*, and *F. verticillioides* using the translation elongation factor 1α (TEF-1α) gene. In the study, several morphologically identified *F. verticillioides* isolates were reidentified as *F. andiyazi*, and morphologically identified *F. subglutinans* was reidentified as *F. sacchari* by means of the TEF-1α sequences. Accordingly, Heng et al. [38] stated that the use of morphological characteristics for identification of *Fusarium* species in the *F. fujikuroi* species complex from the three crops will lead to incorrect species assignment. Correct species identification of *Fusarium* spp. from agricultural crops is useful because it can give information on the prevalence of mycotoxigenic fungi.

**Fusarium mycotoxins in agricultural products, food, and feed**

Malaysia imports cereal grains including corn, wheat, barley, and oats for food and feed because Malaysia does not produce these cereal grains. Corn is planted in Malaysia but on a small scale and is mainly intended for local consumption, not for animal feed. Other cereal grains are used to make cereal-based products or serve as animal feed. These cereal grains are susceptible to mycotoxin contamination because mycotoxigenic *Fusarium* can grow in the field as well as during storage, transportation, and even marketing. Many *Fusarium* mycotoxins including ZEA, DON, FUMs, T2 toxin, and HT2 toxin are associated with cereal grains and cereal-based products.

**Fusarium mycotoxins in cereal grains**

Soleimany et al. [39] found that rice, maize, and wheat samples from different markets in Kuala Lumpur are contaminated with three FUMs, which are FB₁, FB₂, and FB₃. A high concentration of total FUM was detected in wheat samples (80.63 ng/g). FUM contamination of rice samples ranged from 27.85 to 74.67 ng/g, and in maize samples, it was ~56.98 ng/g. Besides FUMs, other mycotoxins detected in rice, maize, and wheat samples are ZEA, DON, T2 toxin, and HT2 toxin. In studies by Soleimany et al. [40, 41], they detected *Fusarium* mycotoxins in samples of cereal grains on the Malaysian market, where DON, FB₁, FB₂, and T2 and HT2 toxins were detected in rice, wheat, barley, oats, and maize meal samples. ZEA was detected in all the cereal samples tested except oats. Soleimany et al. concluded that 77% of cereal samples collected in their study are contaminated with at least one of the mycotoxins under study [41].
Fumonisins in rice

Rice is a staple food in Malaysia, and approximately 30–40% of rice is imported, mainly from Thailand, India, Vietnam, and China. Farhana Nazirah et al. conducted a study on the prevalence of FUMs in rice grains (marketed in Peninsular Malaysia) comprising imported rice and locally produced rice. The rice samples analyzed were basmati rice, black glutinous rice, brown rice, fragrant rice, parboiled rice, rice grains, white rice, white glutinous rice as well as two types of rice products: rice cake and emping. In the study, the highest total FUM levels, ranging from 80 to 130 μg/kg, were detected in white rice samples originating from Malaysia. Lower total concentration of FUMs (30 μg/kg) was detected in a fragrant rice sample from Malaysia. FUMs were not detected in basmati rice, brown rice, and parboiled rice. Both FB1 and FB2 at concentrations of 10–120 μg/kg were detected only in black glutinous rice, fragrant rice grains, white glutinous rice, and two rice products (rice cake and emping). Co-occurrence of FUMs and aflatoxins was detected in a rice product, emping. The study suggests that although some of the rice samples are contaminated with FUMs, rice marketed in Peninsular Malaysia is considered safe because the concentrations of FUMs detected are below the Malaysian permissible limit.

Zearalenone in cereal grains

Several Fusarium mycotoxins have been detected in cereal grains in Malaysia. Rahmani et al. detected ZEA in rice and barley samples at a concentration of 2.8 to 73.11 and 2.38 to 24.43 ng/g, respectively. Nevertheless, they did not detect ZEA in wheat samples. Rahmani et al. reported that ZEA was detected in 18.3% of the cereal grain samples tested at concentrations ranging from 2.4 to 73.1 ng/g and stated that these values are lower than the European Commission regulatory limits.

Deoxynivalenol in noodles

DON has been detected in several types of commercial noodle products in Malaysia. The noodle types analyzed are yellow alkaline, instant, and white salted noodles. In the study by Moazami and Jinap, none of the white-salted-noodle samples contained any detectable amount of DON. Instant and yellow alkaline noodles contained DON at 1.003 and 1.243 ng/g, respectively. They concluded that the concentration of DON in commercial noodle products is low (0.627–1.243 ng/g) and proposed that the risk of DON exposure among humans as a result of consumption of noodles is negligible.

Fusarium mycotoxins in corn feed

Corn samples used as animal feed have been found to be contaminated with Fusarium mycotoxins. In a survey conducted by Lee-Juien and Li-Mien on the occurrence of mycotoxins in feed varieties from Asian countries, a corn sample from Malaysia was found to contain high concentrations of ZEA and FB2. Binder et al. reported high concentrations of ZEA (1380 μg/kg) and FB2 (2844 μg/kg) in corn used as a feed ingredient from Malaysia. In a study by Reddy and Salleh, FUMs were detected in all corn samples used as animal feed, which were randomly collected in 10 states in Malaysia, and the levels of FUMs ranged from 261 to 2420 μg/kg. They stated that the FUM concentrations were below the internationally permissible limits (<5000 μg/kg) for corn-based animal feed.

Effects of food processing on Fusarium mycotoxins in cereal grains

Besides wheat and corn, Malaysia imports oats, barley, sorghum, and rye. Thus, higher risk of mycotoxin contamination originates in the field because Fusarium spp. are field fungi and infect the grains in the field. Mycotoxins in naturally contaminated cereal grains are not completely destroyed during food processing because mycotoxins are stable metabolites. Various types of food processes may reduce mycotoxin concentration but do not eliminate mycotoxins from the processed cereal grains. Thus, mycotoxins can be carried over to finished food products. Food processes that may affect concentrations of mycotoxins include sorting, trimming, cleaning, milling, brewing, cooking, baking, frying, roasting, canning, flaking, alkaline cooking, nixtamalization (soaking, cooking in an alkaline solution, and hulling of grains), and extrusion cooking. Among these processes, roasting and extrusion cooking have been reported to lower the concentration of mycotoxins via application of high temperature.

Sorting and cleaning

Broken and damaged kernels are often found to contain a mycotoxin. By sorting healthy intact cereal grains from broken and damaged kernels as well as cleaning may help to reduce mycotoxin concentrations. By these processes, the levels of mycotoxins maybe reduced, but the magnitude of reductions varies and is generally dependent on the conditions and the extent of the contamination of the cereal grains. In many cases, infected cereal grains that contain high concentrations of Fusarium mycotoxins are indistinguishable from healthy grains, and sorting cannot be used to remove the contaminated grains. Thus, cleaning is used to reduce the mycotoxin concentrations. Abbas et al. reported that cleaning of scab-infested wheat and barley kernels reduces the levels of DON by 6–19% from initial concentrations of 7.9–9.6 mg/kg. Washing cereal grains with distilled water has been found to reduce...
concentrations of mycotoxins. In a study by Trenholm et al., DON and ZEA contents of barley and corn were reduced by washing three times with distilled water. Cleaning also reduced concentrations of FUMs by 26–69% in corn.

**Milling**

Wheat is imported mainly from Australia and the USA, and corn from Argentina and Brazil. The milling process is conducted in Malaysia, and this country has significant flour- and feed-milling industries. Processed corn mainly serves as livestock feed, and wheat is used to produce wheat flour and is turned into wheat-based products including bread, biscuits, crackers, noodles, baby food, and various local delicacies.

Milling is the process of crushing cereal grains, and the process redistributes mycotoxins from the cereal grains into different mill fractions. During dry milling of various cereal grains, the highest concentrations of mycotoxins including DON and ZEA are found in germ and bran fractions, which are unlikely to be used for food production.

According to Karlovsky et al., ZEA is concentrated in fiber-rich parts of grains, whereas DON contaminates all fractions equally. The largest amounts of FB$_1$ are found in the bran fraction used for animal feed as reported by Katta et al. The smallest amount of FUMs was detected in fractions used for food production, including flaking grits and flour. The smallest amount of FB$_1$ was detected in dry-milled corn fractions.

**Thermal food processing**

Although many mycotoxins are heat stable, higher temperatures used in thermal processing or heat treatment may reduce the levels of mycotoxins in food products. The higher temperature is used in conventional food processing including boiling, baking, canning, frying, and roasting.

**Baking**

Baking is prolonged cooking with dry heat and is used for preparation of wheat-based foods including bread, cake, pastry, tarts, and pie. Reports vary regarding the reduction in DON concentration during food preparation by baking methods. Voss and Snook reported that baking reduces DON concentrations in bread and donuts by ≥50%, whereas DON concentrations are higher in cereal flakes. In contrast, Lancova et al. found that baking at 210°C for 14 min has no significant effect on DON concentration. Baking of Egyptian flat bread using whole-wheat flour at 350°C for 2 min does not reduce DON concentration.

In contrast, Scott et al. stated that baking reduces DON amounts by 24–71% in bread, cookies, and biscuits and by 35% in cookies and biscuits. Reports on the effect of baking on FUMs are contradictory too. Castelo et al. reported that FUM concentrations are not reduced in corn muffins baked at 204°C for 20 min, but baking of corn bread at 232°C for 20 min shows a 48% reduction in levels of FUMs.

**Frying**

Frying is a method of cooking involving oil and is an efficient way to transfer heat to food. The reductive effects of frying on FUM concentrations are variable. Frying tortilla chips at 190°C for 15 min reduces levels of FUMs by 67%, but frying corn masa at 140–170°C for 0–6 min does not reduce FUM levels in the food. Depending on the frying temperature, frying reduces DON amounts by more than 20% in wheat-based foods. For instance, when dough covers are fried at 169°C, the DON concentration reduction is 28%; at 205°C, DON concentration is reduced by 21%; and at 243°C, a 20% reduction is observed.

**Roasting**

Roasting involves dry heat: an open flame, oven, or any other heat sources. Roasting is a high-temperature treatment and causes chemical reduction as well as decreases the concentration of mycotoxins depending on the type of roasting and the temperature applied. During a corn flake process, roasting reduces FUM content by 6–35%. In a study by Castelo et al. on the thermal processing of corn meal, roasting of artificially contaminated and naturally contaminated corn meal samples at 218°C for 15 min resulted in almost a 100% loss of FUMs. Roasting of corn meal at 218°C for 15 min also reduces MON levels by 44.6% as compared to autoclaving of creamed corn at 121°C for 65 min, which reduces MON levels only by 10%.

**Extrusion cooking**

Extrusion cooking is a high-temperature short-time process and is used in the production and development of new food products such as breakfast cereals, snack foods, dietary fiber, and baby foods. The effects of extrusion cooking on concentrations of mycotoxins have been studied fairly well. Decreasing the concentration of mycotoxins by extrusion cooking depends on several factors such as the type and temperature of an extruder, screw type and speed, initial mycotoxin concentration, barrel temperature, moisture content of the raw material, the extrusion mixture, and the use of additives. Castelo et al. reported that extrusion cooking results in a more noticeable loss of FB$_1$ with mixing screws than with nonmixing screws; losses of recoverable FB$_1$ are observed at 120°C and 160°C when mixing screws are used. In an extrusion cooking experiment by Accerbi et al. on wheat grain and flour samples, they found that soaking treatment with sodium bisulfite reduces DON levels from 7.3 to 0.8 mg/g without extrusion and to 0.3 mg/g with an extrusion process.

**Parboiling**

Parboiling is a cooking method where food is partially cooked in boiling water and removed before it is completely cooked. For parboiled rice, parboiling
involves soaking, steaming, and drying the rice grains with husk. Dors et al.\(^7\) evaluated the prevalence of four mycotoxins including DON and ZEA in parboiled rice and found that DON (180 to 400 ppb) is present in 22% of the samples, and ZEA (317 to 396 ppb) in 19% of the samples. In another study, Dors et al.\(^7\) reported that mycotoxins migrate into starchy rice endosperm during the parboiling process, and this approach reduces contamination levels.

Food processing affects concentrations of mycotoxins although most mycotoxins are heat stable. Varying degrees of reduction as well as destruction of mycotoxins can be achieved using different types of thermal food processing. The magnitude of reduction and destruction depends on temperature, time, water, and the type of mycotoxin in the food and feed.

**Conclusion**

Judging by the studies conducted on the occurrence of *Fusarium* spp. on agricultural crops, food, and feed in Malaysia, mycotoxigenic *Fusarium* spp. are widespread. *Fusarium* represents species of field fungi growing on crops before harvest at high water activity levels, and therefore mycotoxins are usually produced before or immediately after harvest\(^7\). It is conceivable that mycotoxigenic *Fusarium* spp. are also found after harvest, particularly during storage. In Malaysia, more studies are needed on the natural occurrence of *Fusarium* mycotoxins in agricultural crops because mycotoxin risk management is beginning in the field.

Given that many isolates of *Fusarium* spp. can produce mycotoxins in culture, there is a strong possibility that the isolates can produce mycotoxins in the host plant. Nonetheless, mycotoxins produced by *Fusarium* spp. in Malaysia may differ from those in other countries because the crops planted are different and agronomic practices are different too. Nevertheless, *Fusarium* may grow and produce mycotoxins when the conditions are suitable, and this situation may pose a threat to the health of humans and animals.

Although concentrations of mycotoxins can be reduced by different types of food processing, mycotoxins are still present in food and feed, and thus it is important to monitor the presence of *Fusarium* mycotoxins in food and feed commodities. Methods of control of fungal growth and for reduction of mycotoxin concentrations during storage and marketing should also be developed. Legislation on certain limits of *Fusarium* mycotoxins in various types of food and feed needs to be enacted to prevent the exposure of humans to mycotoxins. In Malaysia, more research on human exposure to *Fusarium* mycotoxins is needed because the data on this topic are badly lacking. This research is important because it should help to determine the magnitude of exposure to *Fusarium* mycotoxins as well as mycotoxins produced by other mycotoxigenic fungi.

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