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Fusarium toxins of the scirpentriol subgroup: a review

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Abstract Scirpentriol and its seven acetylated derivatives comprise a family of type-A trichothecene toxins produced by several species of *Fusarium* fungi. Out of this group 4,15-diacetoxyscirpenol has attracted most attention. It elicits toxic responses in several species and was detected in a variety of substrates. Out of the three possible monoacetylated derivatives 15-monoacetoxyscirpenol and the parent alcohol scirpentriol received some attention, whereas the remaining members of the family were mentioned in few reports. The present review deals with the structure, biosynthesis, analysis and toxicity of scirpentriol toxins. Formation by *Fusarium* species as well as culture conditions used for toxigenicity studies are reviewed; data about the natural occurrence of scirpentriol toxins in different cereal types, cereal associated products as well as in non-grain matrices including potato and soya bean are reported. Basing on literature reports about the toxicity of scirpentriol toxins an attempt is made to summarise the state of knowledge for risk evaluation for human and animal health.

Keywords Analysis · *Fusarium* · Occurrence · Scirpentriol toxins · Type-A trichothecenes · Toxigenicity

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Abbreviations

DAS	Diacetoxyscirpenol
DON	Deoxynivalenol
FUS-X	Fusarenon-X
F.	*Fusarium*
HT-2	HT-2 toxin
MAS	Monoacetoxyscirpenol
NIV	Nivalenol
SCIRP	Scirpentriol
TAS	3,4,15-Triacetoxyscirpenol
T-2	T-2 toxin

Introduction

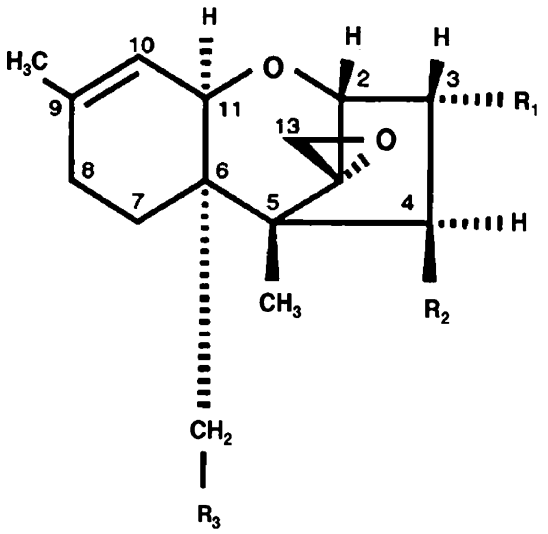
Species of the genus *Fusarium* have been described as widely distributed plant pathogens and producers of a great diversity of toxic secondary metabolites which are of concern for human and animal health. Trichothecenes represent an important class of these mycotoxins. Their structure is characterised by a tetracyclic sesquiterpenoid 12,13-epoxytrichothec-9-ene ring system and a number of hydroxyl and acetoxy groups. At present, more than 170 trichothecenes have been isolated [1]. Based on characteristic functional groups these substances have been divided into A-, B-, C- and D-type trichothecenes. In contrast to B-type trichothecenes, members of the A-type group do not have a carbonyl function at C-8 position. C-type trichothecenes possess a second epoxide function, whereas D-type trichothecenes

contain a macrocyclic ring between C-4 and C-15 with two ester linkages [2].

Scirpentriol (SCIRP) (3α,4β, 15-trihydroxy-12,13-epoxytrichothec-9-ene) and its acetylated derivatives are members of the A-type trichothecenes. SCIRP, the parent alcohol, contains three hydroxyl groups which can be acetylated or unacetylated, thus the scirpentriol family comprises SCIRP, three monoacetoxyscirpenols, three diacetoxyscirpenols and the completely acetylated triacetoxyscirpenol (Fig. 1) [3].

Members of the scirpentriol family were found to be toxic against plants [4, 5], cell cultures [6–8], microorganisms [9, 10] and animals [11–13] resulting from their ability to inhibit protein synthesis [14].

Out of the group of scirpentriol toxins 4,15-diacetoxyscirpenol (4,15-DAS) has been studied the most



Scirpentriol toxin	R_1	R_2	R_3
Scirpentriol	OH	OH	OH
3-Monoacetoxyscirpenol	OAc	OH	OH
4-Monoacetoxyscirpenol	OH	OAC	OH
15-Monoacetoxyscirpenol	OH	OH	OAc
3, 4-Diacetoxyscirpenol	OAC	OAC	OH
3, 15-Diacetoxyscirpenol	OAc	OH	OAc
4, 15-Diacetoxyscirpenol	OH	OAc	OAc
3, 4, 15-Triacetoxyscirpenol	OAC	OAc	OAc

Fig. 1 Chemical structure of scirpentriol toxins

and its toxicity has been found similar to that of T-2 toxin (T-2) [11]. 15-monoacetoxyscirpenol (15-MAS) and SCIRP have received some attention, other members of the group have been rarely investigated. In many publications in which diacetoxyscirpenol and monoacetoxyscirpenol are mentioned the position of the acetyl groups is not specified. Since only 4,15-DAS and 15-MAS were commercially available as standard substances it can be assumed that the terms "DAS" and "MAS" refer to these isomers.

The present review presents data about the structure, biosynthesis, analysis, formation by *Fusarium* species and natural occurrence of scirpentriols. Basing on literature reports about the toxicity of scirpentriol toxins an attempt is made to summarise the state of knowledge for risk evaluation for human and animal health.

Structure and biosynthesis

Trichothecene biosynthesis including that of scirpentriol toxins and its direction by a number of biosynthetic and regulatory genes has been reviewed by different authors [15–17]. Trichothecenes are formed by a series of enzymatic reactions that involve the cyclisation of the isoprenoid-pathway-intermediate farnesyl pyrophosphate to trichodiene by the enzyme trichodiene synthase and the subsequent modification of trichodiene through a series of oxygenation steps [18] to form calonectrin amongst others. The biosynthesis of the scirpentriol group proceeds from calonectrin to 3,15-DAS which is acetylated to form 3,4,15-triacetoxyscirpenol (3,4,15-TAS, synonym 3α-acetyl4,15-diacetoxyscirpenol), which in a next step is deacetylated to 4,15-DAS [15]. By deacetylation at C-4 this substance is transformed into 15-MAS, which is later deacetylated at C-15 to generate SCIRP [19]. Richardson et al. [3] reported the synthesis of all eight members of the scirpentriol family by a culture of *Fusarium sambucinum* NRRL 13495, but no biosynthetic pathways of the toxins 4-MAS, 3-MAS and 3,4-DAS were given.

Analysis

The state-of-the-art in the analysis of type A trichothecenes has been reviewed by different authors [1, 2,

20–23]. Principally, possibilities and problems outlined for type A trichothecenes are valid accordingly also for members of the scirpentriol family. The present article therefore does not cover all published articles but rather attempts to summarise the most common methods in use, focussing on the special situation of scirpentriol toxin analysis.

Most studies described the analysis of DAS, whereas MAS and SCIRP were considered to a lesser extent. The routine analysis of the scirpentriol family is hampered by a lack of commercially available standards. For some years SCIRP, 15-MAS, 4,15-DAS and 3,4,15-TAS were in trade; nowadays to our knowledge only 15-MAS and 4,15-DAS are commercially available.

Different immunochemical methods including enzyme-linked immunosorbent (ELISA) assay systems have been established for determination of trichothecenes [24], and these methods in particular were used for scirpentriol toxin analysis [25]. Due to the low interest in the routine analysis of these substances commercially available kits to our knowledge were not brought to market.

Spectroscopic methods were not applied for the detection of A-type trichothecenes due chiefly to the lack of chromophores in their molecule. To circumvent this limitation chromatographic procedures have been developed [20]. They comprise extraction and clean-up steps prior to measurement of samples.

Various combinations of solvents have been used to extract DAS, MAS and SCIRP from grain, food and feeds. Mostly acetonitrile and water [19, 26–31], or methanol and water [32–34] were described as extractants. For DAS and MAS also ethylacetate was in use [35–37]. Extraction has been performed mainly by high-speed blending or mechanical shaking.

Most clean-up procedures are based on solid-phase extraction. They involve charcoal–alumina columns or modified charcoal alumina columns including charcoal/celite and ion-exchange resin [19, 27–29, 38–42], purification on silica [35, 43], or defatting with hexane followed by purification on Florisil [30]. These methods may be combined with each other or with further clean-up steps based on other chromatographic principles e.g., ion-exchange resin [31, 34] or reversed-phase cartridge [44, 45]. Immunoaffinity columns, which are successfully applied for sample clean-up of several mycotoxins, so far were not used for scirpentriol toxins because of a lack of commercially available columns.

Extraction and clean-up formerly were followed by thin-layer chromatography (TLC) as reviewed by Snyder [20], but gas chromatography (GC) and high-performance liquid chromatography (HPLC) have become increasingly popular. These methods generally are more sensitive, selective, precise and accurate compared to TLC [1].

Gas chromatography methods were based on flame ionisation detection (FID) [36, 46, 47], electron-capture (ECD) [39, 44] or mass spectrometric (MS) detection [19, 27, 29–31, 48–50]. Mostly a derivatisation step of the hydroxyl groups is included in order to increase volatility and sensitivity. Derivatives are trimethylsilyl (TMS) ether [36, 51, 52], heptafluorobutyryl (HFB) ester [46, 48, 53, 54] and the fluoroacyl (trifluoracetyl, pentafluoropropionyl, heptafluorobutyryl) esters [19, 28–31, 39, 40, 49, 50, 55]. Few authors measured the scirpentriols without derivatisation [56]. Up to now the majority of data about the natural occurrence of scirpentriols have been collected using GC methodology.

HPLC-UV detection is not suitable for A-type trichothecenes because of their very low wavelength absorption (below 205 nm) [22]. Therefore pre-column derivatisation methods have been developed including those involving UV detection of the *p*-nitrobenzoate [57] or diphenylindenone sulphonyl esters [58]. Fluorescence measurement of the coumarin-3-carbonyl chloride derivatives also has been applied [59, 60]. Until now these methods are rarely used for analysis of scirpentriols in real samples.

HPLC-MS has a great potential for the simultaneous detection of various mycotoxins and their degradation products [61]. Instruments using electrospray or atmospheric pressure chemical ionisation have been employed for the determination and identification of A-type trichothecenes including scirpentriols at trace levels as recently reviewed by Zöllner and Mayer-Helm [62]. Most articles in this field describe the development of LC-MS methods, which so far only rarely have been used for the collection of data about the occurrence of scirpentriol toxins (Tables 2–7).

MS detection is essential for reliable detection of small quantities of A-type-trichothecenes [21]. GC/MS in contrast to LC-MS is limited to analytes with sufficient volatility. For trichothecene analysis using GC methodology time-consuming and error-prone derivatisation steps are necessary. On the other hand

relatively low separation efficiency of HPLC compared to GC must be taken into consideration when multi-trichothecene analysis especially of mass identical isomers is required [62]. Matrix effects are described for both methods [62, 63]. They require effective sample clean-up, use of internal standard or matrix-assisted calibration.

The typical limits of detection for the determination of DAS, MAS and SCIRP were in the magnitude of 500 µg/kg by TLC, 100–500 µg/kg by GC/FID and GC/ECD, 3–120 µg/kg by GC/MS (Tables 2–7) 0.5–60 µg/kg by HPLC/MS [64–68].

Production of scirpentriol toxins by *Fusarium* species

Previous data have been reviewed by Marasas et al. (1984) [69] and Marasas (1991) [70]. According to these reviews *Fusarium sporotrichioides*, *F. acuminatum* and *F. oxysporum* produced DAS, *F. poae* produced DAS and MAS, *F. semitectum* produced DAS, MAS and SCIRP, *F. equiseti* produced DAS, MAS, SCIRP and TAS *and F. sambucinum* produced DAS, MAS and TAS. The toxigenicity of *Fusarium* species has been reviewed also by Pitt and Hocking (1999) [71] and Leslie et al. (2006) [72].

In Table 1 toxigenicity studies are presented. Mostly DAS was the only toxin of the scirpentriol group which was looked for. This may have resulted from limitations of the analytical method [81] and/or the lack of reference substances. When other scirpentriols were included into the analysis this is indicated, mostly these were MAS and SCIRP, in some cases also TAS. All eight members of the scirpentriol family were found in cultures of different *Fusarium* strains [3, 101].

The taxonomic nomenclature used in publications cited in Table 1 is yet valid [72]. The identification of *Fusarium* strains with few exceptions was based on laboratory manuals, mostly that by Nelson et al. (1983) [102], but also by Burgess and Liddell (1983) [103, 104], Samson et al. (1995) [105], Samson et al. (2000) [106] and Gerlach and Nirenberg (1982) [107]. In some cases fungal strains were supplied or identified by experts, (P. E. Nelson, H. Nirenberg and others), or were obtained from fungal collections. Some identifications were based on publications by Gonzalez et al. (1995) [108], Hestbjerg et al. (1999) [109] and Nirenberg (1995) [110]. The production of scirpentriol toxins by *F. avenaceum* and *F. graminearum* as reported in Table 1 has been questioned [71].

A further problem with regard to the evaluation of studies cited in Table 1 results from the well known

Table 1 Scirpentriol group toxins detected in *Fusarium* cultures and conditions of culturing

	Scirpentriol toxins detected	Scirpentriol toxins not detected	Analyt. method	Substrate	Temp °C	Growth period (days)	Ref.
F. sporotrichioides	DAS[a]		GC/MS	Liquid[b]	22	21	[73]
	DAS		HPLC	Cereals	20,26,33	21	[74]
	MAS[a], 4,15-DAS		HPLC/MS	Solid[c]	15, 25	15–40	[75]
	SCIRP, DAS		GC/MS	Agar[d], wheat	25	7–14	[76]
	SCIRP, MAS, DAS		GC/ECD/MS[e]	Agar, cereals	?,20,25,28	?,7–21	[77]
	15-MAS	DAS	GC//MS	Barley[f]	21–25	3 + 14	[78]
F. chlamydosporum	MAS, DAS		HPLC/MS	Solid	15,25	15,?	[75]
F. poae	DAS		TLC+GC/MS	Liquid	22	21	[73]
	DAS		GC/MS	Rice	25	10	[79]
	4,15-DAS	SCIRP, 15-MAS, TAS	GC/FID	Liquid	22–26	14	[80]
	SCIRP, 15-MAS, 4,15-DAS, TAS		GC/MS	Liquid, rice	28(28 + 10)	10(14 + 14)	[81]
	SCIRP, 15-MAS		GC/MS	Barley[f]	21/25	3 + 14	[78]
	SCIRP, 15-MAS, DAS		GC/ECD/MS[e]	Agar, cereals	?,2025,28	?,7–21	[77]

Table 1 continued

	Scirpentriol toxins detected	Scirpentriol toxins not detected	Analyt. method	Substrate	Temp °C	Growth period (days)	Ref.
F. langsethiae	SCIRP, 15-MAS, 4,15-DAS	TAS	GC/MS	Agar	25	14	[82]
	SCIRP, 15-MAS, DAS		GC/ECD/ MS[e]	Agar, maize	?,2025,28	?,7–21	[77]
F. avenaceum	DAS		GC/MS	Maize	25	28	[83]
F. semitectum	DAS		GC/ECD	Maize	25 + 15	7 + 14	[84]
F. equiseti	DAS		GC/MS	Liquid	22	21	[73]
	SCIRP, 4,15-DAS		GC/MS	Rice	25 + 10	14 + 14	[85]
	MAS, DAS		GC/MS	Liquid ,rice	14/28	28	[86]
	15-MAS, DAS		GC/MS	Agar	25	14	[87]
	SCIRP, MAS, DAS		TLC, GC/ MS	Rice	25–27,+10	14 + 14	[88]
	SCIRP, 15-MAS, DAS		GC/MS	Agar	25	14	[89]
	SCIRP, DAS		GC/MS	Agar,wheat	25	7–14	[76]
	SCIRP, 4-MAS, 15-MAS, DAS	TAS	GC/MS	Agar	25	14	[90]
F. acuminatum	SCIRP, DAS		GC/MS	Agar,wheat	25	7–14	[76]
	DAS		GC/ECD	Corn	25	21	[91]
	SCIRP derivatives[h]		GC/ECD	Liquid[g], solid [c]	25	14	[92]
F. compactum	DAS (main), SCIRP derivatives[h]		GC/ECD	Liquid[g], solid [c]	25	14	[92]
F. sambucinum	DAS		GC/MS	Maize	25	28	[83]
	DAS		LC/HPTLC	Corn	25	28	[93]
	DAS		HPLC	Corn	25	28	[94]
	DAS		LC/MS	Potato	10/20	30/50	[45]
	DAS	15-MAS, TAS	TLC	Agar	25	14	[95]
	DAS		GLC	Liquid	28	7	[96]
	4,15-DAS	15-MAS	GC/FID	Liquid	28	7	[36]
	15-MAS, 4,15-DAS		GC/FID	Potato	25	6	[36]
	4,15-DAS	SCIRP, 15-MAS, TAS	GC/FID	Liquid	22–26	14	[80]
	15-MAS, 4,15-DAS	SCIRP, 4-MAS	TLC	Liquid, wheat	?	28	[37]
	15-MAS, 4,15-DAS	SCIRP, 4-MAS	TLC	Potato	?	28	[37]
	SCIRP, 4-MAS, 15-MAS, 4,15-DAS		GC/MS	Wheat	25	5	[97]
	SCIRP, 4-MAS, 15-MAS, 4,15-DAS, TAS		MS, NMR	Corn	25	21	[98]
	SCIRP, 3-MAS, 4-MAS, 15-MAS		GC/MS, NMR	Liquid	29	3 + 6	[3]
	3,4-DAS, 3,15-DAS, 4,15-DAS, TAS		GC/MS, NMR	Liquid	29	3 + 6	[3]
	SCIRP, 4-MAS, 15-MAS, DAS	TAS	GC/MS	Agar	22–26	14	[90]

Table 1 continued

	Scirpentriol toxins detected	Scirpentriol toxins not detected	Analyt. method	Substrate	Temp °C	Growth period (days)	Ref.
	SCIRP, 4-MAS, 15-MAS, 3,15-DAS,	TAS	TLC, HPLC	Corn	10	21	[99]
F. venenatum	DAS	15-MAS, TAS	TLC	Agar	25	14	[95]
	DAS		HPLC	Corn	25	28	[94]
	4,15-DAS	SCIRP, 15-MAS, TAS	GC/FID	Liquid	22–26	14	[80]
	SCIRP, 4-MAS, 15-MAS, DAS,	TAS	GC/MS	Agar	25	14	[90]
F. culmorum	4,15-DAS[h]	SCIRP, 15-MAS, TAS	GC/FID	Liquid	22–26	14	[80]
F. graminearum	DAS		GC/MS	Maize	25	28	[83]
	DAS		G/MS	Liquid	22	21	[73]
	DAS		GC/ECD	Maize	25 + 15	7 + 14	[84]
	MAS, 4,15- DAS		HPLC/MS	Solid[d]	15,25	15–40	[75]
F. crookwellense[i]	4,15-DAS	SCIRP, 15-MAS, TAS	GC/FID	Liquid	22–26	14	[80]
	DAS		TLC+GC/MS	Corn	25	14	[100]

[a] Position of the acetyl group(s) is not indicated; informations are not available

[b] Liquid medium of varying composition

[c] Liquid medium + vermiculite

[d] Semisynthetic solid medum of varying composition

[e] Norwa:y: GC-MS; Austria: GC-ECD

[f] Greenhouse plants

[g] Cereal biscuits suspended in water

[h] Samples hydrolysed with NaOH to determine trichothecene families

[i] Syn. *F. cerealis*

? Culture conditions not described

fact that the production of fungal secondary metabolites depends not only on genetic informations, but also on a variety of environmental factors. The result of each toxigenicity study therefore must be restricted not only to the fungal strain, but also to the conditions used. In Table 1 some conditions are described.

The duration of growth of cultures up to their analysis for mycotoxins seems to be of importance. Thus, during the growth of a *Gibberella zeae* strain in liquid medium the accumulation of fusarenon-X (FUS-X) and nivalenol (NIV) followed a sequential pattern i.e., at first FUS-X rather than NIV was produced, low levels of nivalenol began to appear midway through the development of *Gibberella zeae* and along with the increase of NIV the concentration of FUS-X decreased [111]. This sequential accumulation is consistent with the observation that acetylated compounds often are formed first and then deacetylated by enzymes produced by the fungi (for literature see Liu et al. [81]). Thus during the growth of a strain of *F. sporotrichioides* in liquid culture the production of deacetylated trichothecenes was associated with an increased activity in fungal esterases [112]. The sequential accumulation of products does not exclude their simultaneous presence during a certain phase of incubation. During toxigenicity studies *Fusarium* cultures mostly were cultivated for 7–21 days prior to their analysis for mycotoxins (Table 1). It cannot be excluded that the investigation of the whole time pattern would have revealed a somewhat other ability for mycotoxin formation. It has been previously suggested [3] that the production of multiple mycotoxins by a single culture is the rule rather than the exception. If this is true the frequently observed co-occurrence of mycotoxins may result not only from the co-occurrence of toxigenic *Fusarium*

strains, but also mainly from the multiple toxin production by a strain.

Another relevant factor is the culture substrate. Here amongst others the availability of a nitrogen source seems to be of importance. Thus the total of eight possible members of the scirpentriol family were detected in nitrogen-free replacement cultures of *F. sambucinum* [3]. These were produced by cultivating the mycelium at first in Czapek-Dox broth and then on the same medium, but without nitrogen source. The reason why this technique apparently favoured the presence of the whole scirpentriol family may have been associated with the absence of a nitrogen source, which possibly affected the enzyme equipment of the cultures. Such an effect was demonstrated for batch cultures of *Aspergillus niger* grown in an extremely nitrogen limited medium in which the nitrogen source was used up shortly after the onset of growth. Under these conditions gluconic acid was accumulated and concomitantly the in vitro activity of a gluconic acid forming enzyme (glucose oxidase) increased, whilst that of enzymes involved in the metabolisation of this secondary product decreased [113]. Likewise, in the replacement cultures of *F. sambucinum* investigated by Richardson et al. [3] the formation of esterases involved in the metabolisation of acetylated scirpentriols may have been retarded by the absence of a nitrogen source this resulting in the presence not only of deacetylated, but also of acetylated products. In contrast, nitrogen rich cultures may favour the formation of esterases [112] this resulting in the prevalence of deacetylated members of the scirpentriol family.

Incubation temperature is a further factor affecting the accumulation of secondary metabolites. According to Park and Chu [75] in general low temperature was preferred to total type-A trichothecene production, with differences between *Fusarium* strains and single toxins. Thus the formation of 4,15-DAS and MAS by *F. sporotrichioides* was either favoured by 15°C compared to 25°C, the yields were similar at both temperatures or even higher at 25° [75]. Mateo et al. [74] incubated *F. sporotrichioides* at 20, 26 or 33°. In both maize and rice, the biosynthesis of DAS increased as incubation temperature decreased, whereas in wheat, the temperature for maximum accumulation was 26°C. Esterase activities in extracts obtained from cultures of *F. sporotrichioides* grown at 15°C were very weak compared to 25°C [112]. *Fusarium* cultures screened for toxigenicity mostly were incubated at temperatures between 20°C and 25°C. Sometimes they were incubated in two steps at medium (20–28°C) and then at lower (10, 15°C) temperatures (Table 1).

Natural occurrence of scirpentriol toxins

Cereals and associated products

Data about the occurrence of DAS are available for North and South America as well as Europe, whereas only few reports exist for Africa, Asia and Australia. The occurrence of DAS in European cereals described before 1995 has been reviewed by Pettersson [114]. Subsequent reports for this region and for other continents are summarised in Table 2, occurrence data about scirpentriols in cereal associated feeds and foods are shown in Table 3. Wheat was the matrix most frequently analysed, followed by oats, barley, corn, corn products, corn plant, corn silage and some other substrates. In wheat, oats, barley and corn DAS was not detected in many investigations although the detection limit of the methods applied mostly was $\leq$30 µg/kg. Thus this toxin was not detected in any sample of wheat, barley and oats from Germany although 721, 240 and 395 samples, respectively, harvested during 5 or 6 years were analysed and a GC-MS method with a low detection limit was used [119, 120, 124, 125, unpublished]. The incidence of DAS was very low (0.3%) also in 169 wheat and 178 oats samples harvested in Norway, which were analysed by GC-MS with a detection limit <20 mg/kg [27]. No DAS was detected in corn plant, corn silage and grain-based food from Germany [50, 121], low incidences and levels were described also for rice bran, cereals and beer. It was only for wheat from Canada, barley from Poland and corn from New Zealand, analysed by GC/MS, that higher incidences of DAS (38%, 80% and 30%, respectively) were found [29, 34, 48]. Toxin levels in wheat, barley, oat and corn samples ranged up to several hundred µg/kg based not only on TLC, GC/FID, GC/ECD, but also on GC/MS (Tables 2, 3).

Compared to DAS a distinctly lower number of data sets are available for the occurrence of MAS in cereals and associated products originating from Canada and Europe; these results are mainly

Table 2 Occurrence of DAS in cereals

Commodity	Country	Method	S[a]	n[b]	%[c]	DL[d] µg/kg	QL[e] µg/kg	Range[f] µg/kg	Ref.
Wheat[g]	Canada	GC/MS	x	53	38			<50–80	[48]
Wheat	Canada	GC/ECD/MS	–	99	0	500/100			[40]
Wheat	Canada	GC/MS	–	193	0		100		[115]
Wheat	Argentina	TLC	–	261	10	500		793[h]	[116]
Wheat	Brazil	GC/FID	–	20	5	100		600	[46]
Wheat	Japan	TLC/ GC-FID/ECD	x	18	0	80–500			[117]
Wheat	Finland	GC/MS	–	134	0	5–25	25–50		[118]
Wheat, soft	France	GC/MS	–	225	0	30	60		[118]
Wheat, durum	France	GC/MS	–	97	0	30	60		[118]
Wheat	Germany	GC/MS	x	721	0	3			[119, 120]
Wheat	Germany	GC/MS	x	41	0	14	28		[121]
Wheat	Germany	HPLC/MS	x	100	0	0.5			[68]
Wheat	Italy	HPLC/MS	x	14	21	20		<100–180	[60]
Wheat	Norway	GC/MS	–	169	0	<20			[27]
Wheat	Romania	ELISA	–	25	0	2			[122]
Barley	Canada	GC/ECD/MS	–	116	0	500/100			[39]
Barley + fractions	Canada	GC/MS	–	56	0		50		[123]
Barley	Japan	TLC/ GC/FID-ECD	x	25	0	80–500			[117]
Barley + malt	Finland	GC/MS	–	145	0	5–25	25–50		[118]
Barley, malting	France	GC/MS	–	194	0	30	60		[118]
Barley	Germany	GC/MS	x	240	0	3			[124, Müller et al., unpublished data]
Barley	Germany	GC/MS	x	15	0	14	28		[Schollenberger et al., unpublished data]
Barley	Norway	GC/MS	–	102	0	<20			[27]
Barley[g]	Poland	GC/MS	–	15	73	10		10–34	[29]
Oats	Canada	GC/ECD/MS	–	73	0	500/100			[39]
Oats	Finland	GC/MS	–	72	0	5–25	25–50		[118]
Oats	Germany	GC/MS	x	17	0	14	28		[121]
Oats	Germany	GC/MS	x	395	0	3			[125, Müller et al., unpublished data]
Oats	Germany	HPLC/MS	x	20	0	0.5			[68]
Oats	Norway	GC/MS	–	178	0.6	<20		Traces	[27]
Oats	Poland	GC/MS	–	99	12	10		10–118	[28]
Rye	Finland	GC/MS	–	33	0	5–25	25–50		[118]
Corn	Canada	GC/ECD/MS	–	673	0.5	500/100		490–1000	[40]
Corn	New Zealand	GC/MS	–	20	30	5–10		10–900	[34]
Corn, imported	Taiwan	GC/FID	–	311	0				[123]
Corn	France	GC/MS	–	25	0	30			[118]
Corn	Germany	GC/MS	x	41	5	14	28	21–76	[121]
Corn	Romania	ELISA	–	30	3	2		2.6	[122]
Rice	Taiwan	GC/FID	–	428	0				[126]

Table 2 continued

Commodity	Country	Method	S[a]	n[b]	%[c]	DL[d] µg/kg	QL[e] µg/kg	Range[f] µg/kg	Ref.
Rice	United Kingdom	GC/MS	–	100	0		10		[118]
Cereals	Lithuania	GC/MS	x	159	0.5	<20		<5	[127]
Cereal fractions	United Kingdom	GC/MS	–	27	0		10		[118]

[a] Specification of isomer, x: 4,15-DAS, –: not mentioned

[b] Total number of samples analysed

[c] Percentage of positive samples

[d] Detection limit

[e] Quantification limit

[f] Range of toxin contents detected

[g] Naturally infected

[h] Average of samples positive

Table 3 Occurrence of DAS in cereal associated foodstuffs and feedstuffs

Commodity	Country	Method	S[a]	n[b]	%[c]	DL[d] µg/kg	QL[e] µg/kg	Range[f] µg/kg	Ref.
Wheat products	United Kingdom	GC/MS	–	95	0		10		[118]
Corn-based food	Brazil	GC/MS	–	78	0	20–120	60–550		[42]
Corn plant + silage	Germany	GC/MS	x	13	0	14	28		[121]
Corn products	Germany	GC/MS	x	13	8	14	28	21	[121]
Corn feed	Italy	HPLC/MS	x	7	29	20		376–847	[66]
Corn products	United Kingdom	GC/MS	–	70	0		10		[118]
Corn products	United Kingdom	GC/MS	–	27	0	10			[49]
Corn gluten	United Kingdom	GC/MS	–	40	5	10		70–200	[49]
Rice bran	United Kingdom	GC/MS	–	40	0		10		[55]
Beer	Argentina	GC/ECD	–	50	0		2		[44]
Food	Japan	TLC/GC/FID-ECD	–	197	0	80–500			[117]
Food	Germany	GC/MS	x	61	0	14	28		[50]
Food	United Kingdom	GC/MS	–	185	0		10		[118]
Suspect feed	USA	GC/MS	x	9	22			380–500	[51]
Feedstuffs	Taiwan	GC/FID	–	160	0				[126]
Poultry feed	Slovakia	HPLC/MS/MS	–	50	20	0.3		−5	[128]

[a–f] See Table 2

collected using GC-MS methodology (Table 4). In wheat, oats and barley MAS mostly was not detected, incidences were $\leq$29% though the detection limit of the methods used were $\leq$30 µg/kg. For corn plants and corn silage a marked higher incidence of 62% was determined [121]. Toxin levels were less than 100 µg/kg.

Scirpentriol was rarely analysed, all results were based on GC-MS and were collected for Europe (Table 5). SCIRP was detected in many cases in contrast to DAS and MAS. For European oats incidences between 3% and 100 % and levels up to 760 µg/kg were reported including 12 oat samples naturally contaminated with *F. poae* and *F. sporotrichioides* in which the mean concentration of SCIRP was higher than the mean concentrations of T-2, HT-2, T-tetraol and DAS [19]. In corn and corn products from Germany SCIRP was found in 15–75% of samples with amounts up to 916 µg/kg in corn plants destined for feed use [121].

Table 4 Occurrence of MAS

Commodity	Country	Method	S[a]	n[b]	%[c]	DL[d] µg/kg	QL[e] µg/kg	Range[f] µg/kg	Ref.
Wheat	Canada	GC/MS	x	30	0		100		[40]
Wheat, soft	France	GC/MS	–	225	0	30	60		[118]
Wheat, durum	France	GC/MS	–	97	0	30	60		[118]
Wheat	Germany	GC/MS	x	41	2	3	6	6	[121]
Wheat	Germany	HPLC/MS	x	100	0	2			[68]
Wheat	Norway	GC/MS	x	169	0	<20			[27]
Barley	Canada	GC/MS	x	30	0		100		[39]
Barley	France	GC/MS	–	194	0	30	60		[118]
Barley	Germany	GC/MS	x	15	13	3	6	5	Schollenberger et al., unpublished data
Barley	Norway	GC/MS	x	102	0	<20			[27]
Oats	Canada	GC/MS	x	20	0		100		[39]
Oats	Germany	GC/MS	x	17	29	3	6	−27	[121]
Oats	Germany	HPLC/MS	x	20	0	2			[68]
Oats	Norway	GC/MS	x	178	0.6	< 20		Traces	[27]
Corn	Canada	GC/ECD/MS	x	142	0		100		[40]
Corn	France	GC/MS	–	25	0	30			[118]
Corn	Germany	GC/MS	x	41	22	3	6	5–51	[121]
Corn products	Germany	GC/MS	x	13	15	3	6	22–39	[121]
Corn plant + silage	Germany	GC/MS	x	13	62	3	6	−85	[121]
Corn products	United Kingdom	GC/MS	–	27	22	10		10–20	[49]
Corn gluten	United Kingdom	GC/MS	–	40	3	10		10	[49]
Rice bran	United Kingdom.	GC/MS	–	40	0		10		[55]
Cereals	Lithuania	GC/MS	x	159		<20		−27	[127]
Grain-based food	Germany	GC/MS	x	61	0	3	6		[50]
Potato products	Germany	GC/MS	x	21	14	3	6	5–26	[50]
Vegetables, fruits	Germany	GC/MS	x	64	0	3	6		[50]
Oilseeds, nuts	Germany	GC/MS	x	35	0	3	6		[50]
Soy food	Germany	GC/MS	x	45	9	3	6	5–34	[129]
Non-cereal feedstuffs	Germany	GC/MS	x	95	3	3	6	5	[121]
Grain dust	Norway	GC/MS	–	104	0	20			[130]

[a] Specification of isomer, x: 15-MAS, –: Not mentioned

[b–f] See Table 2

Very little is known about the natural occurrence of the five remaining members of the scirpentriol group. Lauren et al. [132] and Lauren and Agnew [133] made an attempt to determine the sum of scirpentriols by hydrolysing the scirpentriol esters using NaOH and measuring the resulting alcohol SCIRP. Determinations in corn, wheat, barley and oats showed that scirpentriol toxins are uncommon in cereals from New Zealand (Table 6).

Non-grain substrates

Scirpentriol toxins were found in soya beans and potatoes, a variety of outcoming products and some other commodities (Tables 4, 5, 7).

Fusarium rot of soybeans has been described and species of this genus have been isolated from this commodity able to produce a broad spectrum of toxins including zearalenone and trichothecenes of

Table 5 Occurrence of scirpentriol

Commodity	Country	Method	n[a]	%[b]	DL[c] µg/kg	QL[d] µg/kg	Range[e] µg/kg	Ref.
Wheat	Germany	GC/MS	41	5	8	16	–22	[121]
Wheat	Norway	GC/MS	169	0.6	<20			[27]
Wheat	Poland	GC/MS	248	1	10		10–30	[19]
Barley	Germany	GC/MS	15	13	8	16	12–30	Schollenberger et al., unpublished data
Barley	Norway	GC/MS	102	0	<20			[27]
Barley	Poland	GC/MS	32	37	10		10–83	[19]
Oats	Germany	GC/MS	17	53	8	16	–161	[121]
Oats	Norway	GC/MS	178	3.4	<20		–49	[27]
Oats[f]	Poland	GC/MS	12	100	10		30–760	[19]
Oats	Poland	GC/MS	99	8	10		10–43	[19]
Corn	Germany	GC/MS	41	15	8	16	–97	[121]
Corn products	Germany	GC/MS	13	15	8	16	24–38	[121]
Corn plant + silage	Germany	GC/MS	13	46	8	16	–916	[121]
Cereals	Lithuania	GC/MS	159		< 20		–30	[127]
Grain-based food	Germany	GC/MS	61	0	8	16		[50]
Potato products	Germany	GC/MS	21	10	8	16	23–35	[50]
Banana fruit[f,g]	India	TLC					–418.000	[131]
Vegetables, fruits	Germany	GC/MS	64	0	8	16		[50]
Oilseeds, nuts	Germany	GC/MS	35	0	8	16		[50]
Soy food	Germany	GC/MS	45	4	8	16	25–108	[129]
Non-cereal feedstuffs	Germany	GC/MS	95	1	8	16	21	[121]

[a] Total number of samples analysed

[b] Percentage of positive samples

[c] Detection limit

[d] Quantification limit

[e] Range of toxin contents detected

[f] naturally infected

[g] Palmitoylscirpentriol

Table 6 Occurrence of the sum of scirpentrioltoxins

Commodity	Country	n[a]	%[b]	DL[c] µg/kg	QL[d] µg/kg	Range[e]	Ref.
Corn	New Zealand	91	Few		20		[132, 133]
Wheat	New Zealand	192	Uncommon				[133]
Barley	New Zealand	85	Uncommon				[133]
Oats	New Zealand	29	Uncommon				[133]

[a–e] See Table 6

the A- and B-type [71, 135]. DAS was found in naturally infected soybeans [38]. Out of 13 samples of soya meal one sample each was positive in low concentration for SCIRP or 15-MAS, whereas 4,15 DAS was not detected [121]. Little information exists about the occurrence of scirpentriol toxins in soy-based foodstuffs. According to Schollenberger et al. [129] out of 45 samples of such products analysed by GC/MS two, four and one samples were positive for SCIRP, 15-MAS and 4,15-DAS, with

Table 7 Occurrence of DAS in non-grain substrates

Commodity	Country	Method	S[a]	n[b]	%[c]	DL[d] µg/kg	QL[e] µg/kg	Range[f] µg/kg	Ref.
Soybean[g]	Canada	GC/MS	–	30	0	50			[53]
Suspect soybean	USA	GC/MS	–	24	21			15–230	[38]
Soy food	Germany	GC/MS	x	45	2	14	28	21	[129]
Potato tuber[g]	France	TLC	–	50	80			−140 000	[134]
Potato products	Germany	GC/MS	x	21	5	14	28	21	[50]
Banana fruit[g]	India	TLC	–					−14.000	[131]
Vegetables, fruits	Germany	GC/MS	x	64	0	14	28		[50]
Oilseeds, nuts	Germany	GC/MS	x	35	0	14	28		[50]
Feedstuffs	Germany	GC/MS	x	95	0	14	28		[121]
Grain dust	Norway	GC/MS	–	104	6	10		−37	[130]
Dust	Canada	TLC	–			0.4–4		Pos	[32]
Crude building materials	Finnland	HPLC/MS	–	79	6	2		14–3300	[33]

[a–g] See Table 2

maximum concentrations of 108, 35 and 21 µg/kg, respectively. In two of these samples the combination SCIRP/15-MAS was detected (Table 7).

Dry rot of potatoes is usually caused by *Fusarium* species, particularly *F.solani var. coeruleum* and *F. sulphureum (=F. sambucinum)* leading to significant losses during storage [135, 136]. Different strains producing scirpentriol toxins were isolated from potatoes. Steyn et al. [98] identified 4,15-DAS as dominating compound, and in addition 4-MAS, 15-MAS and 3,4,15 TAS. Several authors artificially infected potato tubers with toxigenic *Fusarium* strains isolated from potatoes and investigated the progress of infection as well as the distribution of DAS and in some cases of MAS in potato tissue [37, 45, 137]. Significant toxin amounts were found in the rotten tissue, but also healthy looking parts were contaminated with DAS in concentrations of up to 110 µg/kg [45]. Desjardins and Plattner [36] examined potato tissue without visible rot injury adjacent to the rotted part of the tuber and found 100 µg/kg of 4,15-DAS also in this tissue compared to 1890 µg/kg in the rotted part. This suggests that the usual practice of cutting out rotted tissue may not always be effective to remove entirely the trichothecenes from tubers infected with *Fusarium* strains. Other members of the scirpentriol family were not included into the studies though Latus-Zietkiewics et al. [37] reported that the extracts of cultures containing mycotoxins were more toxic to *Artemia salina* larvae than it had been expected according to 4,15-DAS concentrations detected in these extracts by TLC analysis.

Information about the natural occurrence of trichothecenes in potatoes and potato derived food products infected with *Fusarium* species is very limited. DAS was found in potato tubers with dry rot sampled in France at an incidence of 80% and concentrations up to 140 mg/kg [134]. The authors found high concentrations in rotted tissue, whereas adjacent not rotted tissue contained DAS between <0.05 and 11 mg/kg. Out of 21 potato-based foodstuffs marketed in Germany 1, 3 and 2 samples contained 4,15-DAS, 15-MAS and SCIRP, with maximum contents of 21, 26 and 35 µg/kg, respectively (Tables 4, 5, 7).

Concerning other non-grain based matrices Chakrabarti and Ghosal [131] reported amounts of up to 418 mg/kg of palmitoylscirpentriol, a derivative of SCIRP, in naturally infected banana fruits, determined by TLC. Beardall and Miller [138] reviewed the occurrence of trichothecene toxins in different matrices and reported the detection of DAS in peanut and safflower analysed by TLC. No 4,15-DAS and SCIRP was detected in several non-cereal based foodstuffs and feedstuffs from the German market [50, 121], 15-MAS was found in traces in lupine samples [121].

Sick building syndrome

Sick building syndrome is a complex chronic and multifactorial set of health problems, possibly related to the air conditioning of occupied spaces [32]. Several air contaminants such as aero-allergens,

organic and inorganic dust, fibres, tobacco smoke, gases and microbials are suspected to be factors leading to chronic health problems in "sick buildings". The symptoms of airborne toxicoses involve headaches, chronic fatigue, cold and flu-like reaction, dermal irritation and others. Several authors have pointed to an analogy between the symptoms of sick buildings and the outbreaks of trichothecene toxicosis. The study of Smoragiewicz et al. [32] showed the presence of trichothecene mycotoxins in dust samples from ventilation systems of occupied spaces reportedly affected by the sick building syndrome. DAS and SCIRP were detected as main trichothecenes. Tuomi et al. [33] analysed samples of moldy interior furnishes from Finnish buildings with moisture problems by HPLC/MS and detected concentrations of DAS up to 3.300 µg/kg. In this context it must be taken into consideration that intoxication by inhalation is generally estimated to be as much as 40 times more efficient than intoxication by oral exposure [32].

Discussion

From a global perspective data about the occurrence of 4,15-DAS, 15-MAS and SCIRP are limited with most studies available for North and South America as well as Europe. No informations exist about the incidences of the other members of the scirpentriol family.

It must be kept in mind that the significance of occurrence data depends on the analytical method applied. As described above a spectrum of methods was used for data collection. Studies based on high detection limits allow for a first insight. Data collected using methods with low detection limit such as GC-MS and HPLC-MS seem essential to evaluate the contamination of food and feedstuffs.

Most information exists about the occurrence of scirpentriols in grain and derived products. The examination of non-grain based foods and feeds was widely neglected. Substrates important for the consumption of scirpentriol toxins may include amongst others soybeans and soybean products as well as potatoes and their products. In some reports scirpentriol toxins were detected in those matrices even in high amounts (Tables 4, 5, 7).

The global per caput supply of soybeans and products varied between 0 and 13 g per person per day for European and Far Eastern diet, respectively [139]. The widespread use of soyproducts in infant food formulas and the significant consumption of soyproducts by people consuming a vegetarian diet [140] may result in a relatively high contribution of soybean intake to the total exposure of those consumers to scirpentriol toxins. Potatoes and derived products are main sources of human food throughout the world. Their global consumption varied between 19 g and 241 g per person per day for Far East and Europe, respectively, compared to 178 g per day of wheat and derived products in Europe [139]. This high consumption by humans and the usage of potatoes for animal nutrition together with their susceptibility against *Fusarium* rot raises the question of the concern of their contamination with *Fusarium* toxins for human and animal health. Overall data available at present about the natural occurrence of scirpentriol toxins in soya beans and potatoes and derived products are not sufficient to evaluate the health risk. Further data are needed including the occurrence of the whole sprectrum of scirpentriol toxins. Furthermore informations about the role of these toxins for the sick building syndrome also are urgently needed.

Little is known about the co-occurrence of DAS, MAS and SCIRP. Langseth and Rundberget [27] assumed that the content of acetoxyscirpentriols in cereals generally is below that of the deacetylated form, scirpentriol. This is consistent with the above-mentioned formation of esterases [112]. However, the deacetylation process may be incomplete. This is suggested by the incidence of DAS, MAS and SCIRP in wheat, barley, oats and corn which can be deduced from reports which used methods with a detection or quantification limit $\leq$30 µg/kg (see Tables 2, 4, 5). Based on a total of 3453, 1224 and 954 of cereal samples the incidence of DAS, MAS and SCIRP was at 1.1%, 1.5% and 6.3%, respectively. The relative content of acetylated isomers and SCIRP may depend on a variety of genetic and environmental factors, one of these factors being the period between the onset of *Fusarium* growth in infected cereals and their harvest. For non-grain substrates a ranking of scirpentriol toxins with regard to their occurrence is not possible because of a substantial lack of data.

The toxicity of all members of the scirpentriol group has been investigated by Richardson and Hamilton [12]. Out of the eight scirpentriols 4,15-DAS was most toxic for guinea pigs (dermal toxicity), brine shrimps and chickens. The relative toxicity of the other scirpentriols varied dependent on the test system. For chickens following oral application the LD_{50} of 4,15-DAS, 15-MAS, TAS and SCIRP was at 2.0, 2.5, 7.2 and 9.3 mg/kg body weight, for *Artemia salina* the LC_{50} (dose killing 50% of the nauplii) was at 121, 243, 284 and 346 ng/ml, and the minimum effective dose (MED) for dermal toxicity in guinea pigs was at 50, 400, 150 and 1,800 ng, respectively. The toxicity of the other scirpentriols ranged up to an LD_{50} in chickens of >32.0 (3,4-DAS), to an LC_{50} in brine shrimps of 2294 ng/ml (3-MAS) and to an MED of dermal toxicity of 5200 ng (3-MAS). According to Mirocha et al. [101] 4,15-DAS was somewhat more toxic to egg embryos than TAS and MAS, with LD_{50} values of 123, 232 and 189 ng/egg, respectively. With both chicks and rats these authors found 15-MAS most active followed closely by 4,15-DAS and TAS. In chicks (oral application) LD_{50} values of TAS, 4,15-DAS and 15-MAS were at 8.0, 5.9 and 3.4 mg/kg, in rats (oral application) 2.3, 1.6 and 1.8 mg/kg, respectively. For comparison, Ueno [11] reported the LD_{50} of orally applicated DAS and T-2 for chickens at 3.82 mg/kg and 4.97 mg/kg, respectively, and according to Thompson and Wannemacher [6] LD_{50} values of 4,15-DAS, 15-MAS, T-2 and DON to mice (intraperitoneal application) were at 15.3, 4.5, 9.1 and 43 mg/kg body weight, respectively. This strongly suggests that the toxicities of 4,15-DAS, 15-MAS, TAS and SCIRP are similar to that of T-2. It must be stressed that an exact comparison of the toxicity of scirpentriols, T-2, HT-2 and other trichothecenes including DON, NIV and FUS-X so far is not possible because to our knowledge no investigation has been published which used the same test system for all these toxins.

It must remain open to which extent the scirpentriols contribute to the risk posed by mycotoxins in foods and feeds on human and animal health. This risk depends on a multitude of factors. For cereals and associated products the contamination with scirpentriol toxins seems to be much weaker than that of other trichothecenes such as DON [2]. However, non-grain commodities should be kept in mind. Thus potatoes in some cases were strongly contaminated with the highly toxic DAS (Table 7).

An important question refers to the co-occurrence of scirpentriols with other *Fusarium* toxins. It cannot be excluded that a sample with a low content of DON and/or T-2 is contaminated with highly toxic scirpentriols, dependent on its infestation with *Fusarium* strains and production conditions. This is a further argument in favour of a worldwide study of the occurrence of these latter toxins.

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