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Review

Effect of Organic and Conventional Cereal Production Methods on *Fusarium* Head Blight and Mycotoxin Contamination Levels

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Abstract: *Fusarium* mycotoxins in cereals constitute major problems for animal and human health worldwide. A range of plant pathogenic *Fusarium* species that can infect cereal plants in the field are considered the most important source of mycotoxins, such as deoxynivalenol (DON), zearalenone (ZEA), T-2 toxin, and HT-2 toxin, in small-grain cereal crops in temperate climates. In this article, we (i) critically review the available knowledge on the impact of contrasting production systems (organic versus conventional) and specific agronomic parameters on the occurrence and concentrations of DON, ZEA, and T-2/HT-2 in small-grain cereals (wheat, oats, barley, and rye), and (ii) discuss *Fusarium* mycotoxin risks in the context of the need to develop more sustainable cereal production systems. Overall, the available evidence from studies of acceptable scientific quality suggests that the incidence and concentrations of *Fusarium* mycotoxin are lower in organic compared with conventional cereals. Specifically, 24 comparisons showed lower mycotoxin levels in organic production, 16 detected no significant difference, and only 2 showed higher levels in organic production. When the mean concentrations from all studies were compared, conventionally produced cereals had 62%, 110%, and 180% higher concentrations of DON, ZEA, and T-2/HT-2, respectively, than organic cereals. Overall, published studies on the effects of specific agronomic practices on mycotoxin levels suggest that diverse crop rotations and high soil organic matter content/biological activity are associated with a lower risk of *Fusarium* mycotoxin contamination, whereas (i) high mineral nitrogen fertiliser inputs, (ii) some fungicides and herbicides, and (iii) minimum or no tillage may increase the risks of *Fusarium* mycotoxin contamination in cereals. The management of *Fusarium* head blight and mycotoxins, therefore, requires a preventative, integrated, holistic agronomic approach.

Keywords: *Fusarium* head blight; *Fusarium* mycotoxins; deoxynivalenol (DON); zearalenone (ZEA); T-2 toxin; HT-2 toxin; organic cereal production; conventional cereal production; agronomic practices

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Citation: Bernhoft, A.; Wang, J.; Leifert, C. Effect of Organic and Conventional Cereal Production Methods on *Fusarium* Head Blight and Mycotoxin Contamination Levels. *Agronomy* **2022**, *12*, 797. https://doi.org/10.3390/agronomy12040797

Academic Editor: Sambasivam Periyannan

Received: 23 February 2022
Accepted: 23 March 2022
Published: 26 March 2022

1. Introduction

Mycotoxin contamination of cereals constitute major problems for animal and human health worldwide [1]. There is a particular concern about mycotoxins produced by plant pathogenic *Fusarium* species that can infect growing cereal species, such as wheat (*Triticum aestivum*), oats (*Avena sativa*), barley (*Hordeum vulgare*), rye (*Secale cereale*), and maize (*Zea mays*), and cause *Fusarium* head blight (FHB); these pathogenic *Fusarium* species are considered to be the most important source of mycotoxin contamination in small grains in temperate climates. The type and ranges of mycotoxins produced differ between *Fusarium* species associated with FHB; specifically, deoxynivalenol (DON) and zearalenone (ZEA) are primarily produced by *F. graminearum* and *F. culmorum*, while T-2 toxin and HT-2 toxin contaminations are considered to be mainly caused by *F. langsethiae*, *F. poae*, and *F. sporotrichioides* [1–4].

Exposure to DON is considered to pose a significant health risk in humans and livestock and causes gastrointestinal distress and impairment of the immune system via various mechanisms [1]. Exposure to ZEA, which is a potent antagonist of oestrogen receptors, impairs mammalian reproduction and sexual maturity [2]. T-2 and HT-2 are considered to have similar toxicity, which is principally similar but more potent than that of DON. They cause gastrointestinal lesions and immune suppression and may result in death when ingested in high concentrations [3].

For most *Fusarium* mycotoxins, the main (or 'maternal') compounds formed by the fungus as well as several chemical derivatives can be detected in cereal grains. For example, acetylated/deacetylated and conjugated forms of DON and T-2/HT-2 and both reduced and conjugated forms of ZEA may be detected in cereal grains [1–3]. There is evidence that these derivatives may be formed by fungal and host plant metabolism. There is less information about the relative toxicity of these derivatives, but their toxicity can differ significantly from that of the maternal compounds.

DON derivatives (e.g., 3-acetyl-DON, 15-acetyl-DON, DON-3-glucoside) are considered to have the same toxic effect as DON when ingested with cereals. The concentrations of derivatives in grains are usually considerably lower than those recorded for DON, but were reported to correlate with DON concentrations [1]. For derivatives of ZEA and T-2/HT-2, there is less information about relative toxicity and to what extent their concentrations are correlated with the maternal compounds [2,3]. The concentrations of maternal mycotoxins are often used as markers to estimate the levels of the DON, ZEA, and T-2/HT-2 derivatives.

It is also important to point out that cereals may become contaminated in the field with several other mycotoxins that may be produced by *Fusarium* spp. or other plant pathogenic and nonpathogenic fungal species [4]. However, since there is limited information on the effects of a production system and specific agronomic practices on the occurrence of these other mycotoxins (e.g., nivalenol, diacetoxyscirpenol, fusarin C, enniatins, moniliformin, beauvericin, fumonisins, tenuazonic acid, and ergot alkaloids), this review will focus primarily on the three main *Fusarium* mycotoxins (DON, ZEA, and T-2/HT-2).

Weather and climatic conditions are known to have a strong effect on the *Fusarium* infection processes, disease severity, and mycotoxin production in the plant tissues. Thus, the dominant *Fusarium* species and mycotoxin profiles found in cereals are known to differ significantly between (i) growing seasons with contrasting weather conditions and (ii) climate zones [4–11]. Site-specific environmental factors that affect irradiation and humidity (e.g., position in the landscape or proximity to lakes and rivers) can also affect *Fusarium* mycotoxin loads in cereals [4,10].

There is also substantial evidence that a range of specific agronomic parameters, including crop rotation, fertilisation regimes, crop protection products, tillage, and cereal genetics/cultivar choice, affect mycotoxin concentrations in cereal grains [4,7,10,12–15]. It is important to note that many of these agronomic parameters affect mycotoxin production and metabolisms indirectly by generating changes to the soil or aboveground micro-environment or by affecting plant physiology or resistance. In fact, a range of agronomic practices (including monoculture/shorter rotations and minimum or no tillage) and interventions (including use of high mineral N fertiliser inputs, strobilurin fungicides, and the growth regulator chlormequat to reduce straw length) that were introduced to increase yields and/or profitability of cereal production are also now recognised to increase the risk of *Fusarium* head blight (FHB) and grain mycotoxin loads [16,17].

The FAO/WHO Codex Alimentarius Commission (1999) has given the following definition of organic agriculture: 'Organic agriculture is a holistic production management system which promotes and enhances agro-ecosystem health, including biodiversity, biological cycles, and soil biological activity. It emphasises the use of management practices in preference to the use of off-farm inputs, taking into account that regional conditions require locally adapted systems. This is accomplished by using, where possible, agronomic, biological, and mechanical methods, as opposed to using synthetic materials, to fulfil any specific function within the system'.

The specific standards/rules for organic agriculture may vary slightly between different countries but, in general, prohibit the use of all synthetic chemical pesticides (fungicides, herbicides, insecticides), plant growth regulators, and water-soluble mineral N, P, and KCl fertilisers, as well as the use of genetically modified plant varieties/hybrids. Instead, organic farming standards prescribe (i) the inclusion of legume crops in crop rotation and (ii) regular inputs of organic fertilisers (e.g., manure and composts) and (iii) allow moderate inputs of raw phosphate, potassium sulphate, and mineral micronutrient fertilisers if deficiencies are identified by soil or plant analyses [18–22]. As a result, organic and conventional cereal production protocols differ substantially in (i) rotation design, (ii) the crop protection methods used, (iii) the types and quantities of organic and mineral fertilisers applied, and (iv) the types of crop varieties used for production [18–22]. However, it is important to point out that there is also considerable variation between organic arable production protocols concerning, for example, rotation designs, tillage/weed control methods, fertilisation regimes, and variety choice.

There are now a substantial number of scientifically sound studies which compared mycotoxin contamination levels in organic and conventional cereal production, and overall, the available evidence suggests that there are significant interactions between agronomic methods and pedoclimatic environments with respect to both FHB and mycotoxin contamination levels [7,23]. Given the confounding effects of environmental background conditions and variation in agronomic protocols used in both organic and conventional cereal production, it is difficult to determine whether, overall, *Fusarium* mycotoxin contamination is lower, similar, or higher in organic compared with conventional production systems.

Additionally, since different *Fusarium* species were shown to require contrasting environmental background conditions for optimum colonisation, infection, and mycotoxin production in cereals, there is usually a lack of correlation between concentrations of mycotoxins produced by different *Fusarium* species (e.g., between DON and T-2/HT-2) [7,8]. This may also have contributed to the variation observed between comparative studies carried out in different site countries, regions, and/or pedoclimatic environments. However, it is important to point out that the ratio of different mycotoxin concentrations produced by the same *Fusarium* species (e.g., of T-2 and HT-2 produced by *F. langsethiae*, *F. poae*, and *F. sporotrichioides* or DON and ZEA produced by *F. graminearum* and *F. culmorum*) is often fairly constant [7–10,24,25].

The main objective of this review is therefore to summarise and discuss the currently available knowledge on the impact of cereal production systems, conventional versus organic, and specific agronomic practices on the occurrence and concentrations of the main *Fusarium* mycotoxins (DON, ZEA, and T-2/HT-2) in small-grain cereals (wheat, oats, barley, and rye). The effects of specific agronomic practices on mycotoxin contamination risk are also discussed in the context of the need to develop more sustainable cereal production.

2. Materials and Methods

2.1. Literature Search and Review

A literature search (using the databases ScienceDirect and Web of Science) was carried out to identify scientific studies which (a) compared *Fusarium* infection and mycotoxin contamination levels in small-grain cereals from organic and conventional production systems and (b) investigated the effect of specific agronomic parameters/factors (rotation design, fertilisation, crop protection) on *Fusarium* and mycotoxins levels. The keywords used were 'mycotoxins organic*', 'mycotoxin* organic conventional', 'nitrogen mycotoxin* cereals', and 'pesticides mycotoxin* cereals'. The literature on comparison between production systems used for this review was based on studies previously reviewed by Bernhoft et al. [7] and Brodal et al. [23] and complemented more recent publications. The review of studies focused on identifying the effects of specific agronomic parameters was based on recent papers and reviews identified via the database search (see above).

For the review of studies that compared *Fusarium* mycotoxins in organic and conventional cereal grain, we only considered results/data from controlled, replicated field experimental/trials and farm surveys which compared grains collected at harvest from organic and conventional farms. Results from retail/basket surveys which mainly focused on cereal flour or processed cereal products were not considered because they may not accurately reflect differences resulting from contrasting agronomic practices. This is mainly because it is well documented that in retail surveys confounding effects of grain processing, milling methods, and quality assurance systems (which are designed to exclude grains with high mycotoxin levels from use for human consumption) result in substantially lower mycotoxin levels than in farm surveys and field experiments [26].

It should be pointed out that the scope and quality of published studies included in our review varied considerably. For example, some of the trials and surveys were conducted over several years/growing seasons, while others were based on comparisons from only a single season. Some surveys consisted of several hundreds of comparable samples, while some others had far lower numbers of samples.

In the review, we included data from all available published controlled field experiments/trials that compared DON, ZEA, or T-2/HT-2 in grain from organic and conventional agronomic systems if the number of individual or pooled samples from each production system was considered sufficient for statistical analysis ($n \geq 3$), and the mycotoxins assessed were detectable in at least one of the agronomic systems. We included data from all available published field/farm surveys that compared DON, ZEA, or T-2/HT-2 in at least 35 grain samples per cereal species and agronomic system and detected at least 15 positive samples for a specific mycotoxin in at least one of the agronomic systems.

2.2. Estimates of Mean Mycotoxin Concentration

For calculation of the mean concentrations of the specific mycotoxins in all studies, half the limit of detection (LOD) or half the limit of quantification (LOQ) were used for samples that tested negative of specific mycotoxins as previously recommended. For papers that found no significant difference but did not report separate means for each agronomic system, the same mean was used for both agronomic systems.

3. Results and Discussion

3.1. Studies That Compared Mycotoxin Levels in Organic and Conventional Cereal Grains

Most studies that compared *Fusarium* mycotoxin contamination in organic and conventional cereal grain assessed DON as the main marker for *Fusarium* mycotoxin loads. Table 1 summarises the results of field trials and farm surveys that have compared DON in organic and conventional small-grain cereal species.

Table 1. Results from field-experiment- and farm-survey-based studies that compared deoxynivalenol (DON) concentrations in organically (org) and conventionally (con) produced cereal grain.

Study Type Cereal Species	Country	Sampling Year (s)	No. of Samples Org/Con [1]	% Positive Samples Org/Con [1]	Mean Org/Con [1] (µg/kg)	Median Org/Con [1] (µg/kg)	Result of Statistical Analysis	Reference No.
Experiments								
Wheat	Poland	2014			64/85		NS	[27]
Wheat	Canada	2009			3900/5500		O < C	[28]
Wheat	Canada	2010			340/460		NS	[28]
Wheat	Slovakia	2007–2008			192/362		O < C	[29]
Durum	Italy	2006–2008			27/74		O < C	[30]
Wheat	Czechia	2004–2006			151/369 [2]		O < C	[31]
Wheat	Czechia [3]	2004–2006			151/246 [3]		NS	[31]
Wheat	France	2000–2002			270/460		NS	[32]
Wheat	Germany	1999–2001			179/283 [4]		O < C	[33]
Wheat	Switzerland	1998,2000		100/100	49/82		O < C	[34,35]
Wheat	Germany	1997–1998			200/265 [4]		O < C	[36]
Oats	Finland	1997–1998			109/148		NS	[37]

Table 1. *Cont.*

Study Type Cereal Species	Country	Sampling Year (s)	No. of Samples Org/Con [1]	% Positive Samples Org/Con [1]	Mean Org/Con [1] (µg/kg)	Median Org/Con [1] (µg/kg)	Result of Statistical Analysis	Reference No.
Surveys								
Wheat	Czechia	2015–2017	154/330	12/21	<20 [5]/80	<20/<20	O < C	[38]
Wheat [6]	Czechia	2015–2017	154/154 [6]	12/14	<20 [5]/23	<20/<20	NS	[38]
Durum	Spain	2006–2007	50/67	28/31	95/194		NS	[39]
Wheat [6]	Norway	2002–2004	92/92 [6]		86/170	29/51	O < C	[40]
Wheat	Belgium	2002–2003	51/42	96/100	204/493		O < C	[24]
Wheat	UK	2001–2005	247/1377	86	230 [7]	42 [7]	NS	[41]
Wheat	Germany	2000–2007	110/355	23/42	55/242 [4,8]		O < C	[42]
Wheat	Germany	1998	46/150	54/69	760/1540	230/270	O < C	[43]
Wheat	Germany	1991	50/51	76/88	381/376		NS	[44]
Oats [6]	Norway	2002–2004	101/101 [6]		114/426	24/36	NS	[40]
Barley	Switzerland	2013–2014	42/225		24/201		O < C	[13]
Barley	UK	2002–2005	108/338	57 [7]	19 [7]	11 [7]	NS	[45]
Barley [6]	Norway	2002–2004	108/108 [6]		44/44	<20/<20	NS	[40]
Rye	Germany	2000–2007	173/337	14/36	<50 [9]/62 [4,8]		O < C	[42]
Rye	Germany	1991	50/50	56/40	261/94		O > C	[44]

NS, no significant difference; O < C, organic grain samples had significantly lower DON concentrations ($p < 0.05$); O > C, organic grain samples had significantly higher DON concentrations ($p < 0.05$); [1] organic/conventional; [2] mean for conventional is from low- and medium-intensity conventional systems); [3] mean for conventional is from high-intensity conventional systems; [4] mean of data from all years/growing seasons assessed; [5] mean is below the limit of quantification (LOQ); [6] results from paired farm survey; [7] the author reported % positive samples and mean and median concentrations of all samples (organic and conventional); [8] we used ½ limit of detection (LOD) for undetectable samples; [9] mean is below the limit of detection (LOD).

Specifically, there have been 17 studies on wheat, two on oats, three on barley, and two on rye. Three of these studies consisted of two substudies; thus the total number of comparisons considered in our analysis was 27. In 14 (52%) of the comparisons, the DON concentrations were significantly lower in organic production. Twelve comparisons (44%) did not find a statistically significant difference between the agronomic systems, whereas only one comparison (4%) (a 1-year farm survey of rye carried out in 1991 in Germany) reported a significantly higher concentration in organic grain [44].

It is also important to note that in most studies that reported no significant difference between production systems, the mean concentrations were numerically lower in organic grain. The average of the mean concentrations of DON reported in individual studies were 236 and 383 µg/kg in organically and conventionally produced cereal grain, respectively. Thus, the estimated concentration in conventionally produced cereals was 62% higher compared with the estimated concentration for organically produced cereals (Figure 1).

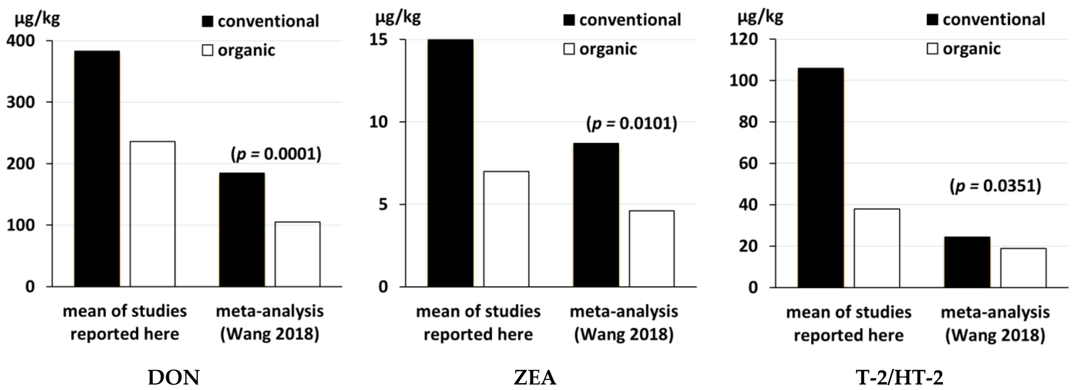

Figure 1. Mean deoxynivalenol (**DON**), zearalenone (**ZEA**), and T-2/HT-2 toxin (**T-2/HT-2**) concentrations found in the field-experiment- and farm-survey-based studies reviewed here (see Tables 1–3) and in a recent systematic review and meta-analyses of data from field-experiment-, farm-survey-, and retail-survey-based studies carried out by Wang (2018) [46].

Table 2 summarises results from studies that compared ZEA concentrations in organic and conventional small grain cereals, and all seven studies available were on wheat. Three studies found a significantly lower concentration of ZEA in organic wheat, and three did not find a statistically significant difference. One study reported significantly higher ZEA concentrations in organically produced wheat, and this is the same study carried out in Germany in 1991 that also reported higher DON levels in organic rye [44].

The average mean ZEA concentrations reported in the seven studies were 7 and 15 µg/kg in organically and conventionally produced wheat, respectively (Figure 1). Thus, the estimated ZEA concentration in conventional wheat grain was 110% higher than the estimated concentration in organically produced wheat.

Table 2. Results from field-experiment- and farm-survey-based studies that compared zearalenone (ZEA) concentrations in organically (org) and conventionally (con) produced cereal grain.

Study Type Cereal Species	Country	Sampling Year (s)	No. of Samples Org/Con [1]	% Positive Samples Org/Con [1]	Mean Org/Con [1] (µg/kg)	Median Org/Con [1] (µg/kg)	Result of Statistical Analysis	Ref. No.
Experiments								
Wheat	Slovakia	2007–2008			8/7		NS	[29]
Wheat	Germany	1999–2001			<5 [2]/28		O < C	[33]
Surveys								
Wheat	Czechia	2015–2017	154/330	4/9	<2 [3]/3	<2/<2	NS	[38]
Wheat	Belgium	2002–2003	51/42	27/45	10/39		O < C	[24]
Wheat	Germany	2001–2007	94/308	5/16	3/11 [4]		O < C	[42]
Wheat	UK	2001–2005	247/1377		17 [5]	<5 [5]	NS	[41]
Wheat	Germany	1991	50/51	36/16	9/1		O > C	[44]

NS, not significant; O < C, organic grain samples had significantly lower ZEA concentrations ($p < 0.05$); O > C, organic grain samples had significantly higher ZEA concentrations ($p < 0.05$); [1] organic/conventional; [2] mean is below the limit of detection (LOD); [3] mean is below the limit of quantification (LOQ); [4] mean of data from all years/growing seasons assessed; [5] the author reported mean and median concentrations of all samples (organic and conventional).

Table 3 summarises studies that compared T-2 and HT-2 mycotoxin levels in grain from organic and conventional production. There are eight studies, two on wheat, four on oats, and two on barley. Seven of the studies found significantly lower toxin concentrations in organic cereal grain, and one study reported no statistically significant difference. The papers reported either the concentrations of the sum of T-2 and HT-2 or separate concentrations for T-2 and HT-2 or only HT-2. In papers where the sum of T-2 and HT-2 was not reported, the concentrations of HT-2 were used to calculate the average mean T-2/HT-2 concentration.

The mean toxin concentrations based on all studies on T-2/HT-2 were 38 and 106 µg/kg in organically and conventionally produced cereals, respectively (Figure 1). Thus, the average mean T-2 + HT-2 (or HT-2) concentration of conventionally produced cereals was 180% higher compared with the estimated concentration in organically produced cereal grain.

It was not surprising that most available data are for wheat, since wheat is the dominant cereal crop used for human consumption in Europe and North America. Additionally, wheat is known to have a lower resistance against *Fusarium* infection compared with other small-grain cereal species [1]. However, it should be pointed out that T-2 and HT-2 are known to be more commonly present in oats than wheat [3].

Table 3. Results from field-experiment- and farm-survey-based studies that compared the sum of T-2 and HT-2 toxin (T-2/HT-2) concentrations in organically (org) and conventionally (con) produced cereal grain.

Study Type Cereal Species	Country	Sampling Year (s)	No. of Samples Org/Con [1]	% Positive Samples Org/Con [1]	Mean Org/Con [1] (µg/kg)	Median Org/Con [1] (µg/kg)	Result of Statistical Analysis	Ref. No.
Experiments								
Wheat	Switzerland	1998–2000		13/44	¼ [2,3]		O < C	[35]
Surveys								
Wheat	UK	2001–2005	247/1377	20/36	<10 [4]/11 [2]		O < C	[41]
Oats	Ireland	2020	114/86	52/74	137/397 [5]		O < C	[47]
Oats	UK	2002–2005	115/343	78/97	50/264	49/292	O < C	[48]
Oats	Germany	2005	35/35	100/100	8/27		O < C	[49]
Oats [6]	Norway	2002–2004	101/101 [6]		80/117 [2]	<20/62 [2]	O < C	[40]
Barley	UK	2002–2005	108/338	36 [2,7]	10 [2,7]	<10 [7]	NS	[45]
Barley [6]	Norway	2002–2004	108/108 [6]		<20 [8]/21[2]	<20/<20 [2]	O < C	[40]

NS, not significant; O < C, organic grain samples had significantly lower H-2/HT-2 concentrations ($p < 0.05$); [1] organic/conventional; [2] values are for HT-2 concentrations only; [3] for calculation of means we used half the limit of detection (LOD) for samples that had concentrations below the LOD and half the limit of quantification (LOQ) for concentrations that were between the LOD and LOQ; [4] mean is below LOQ; [5] mean concentrations of positive samples (above LOQ) were received from the authors (exact concentrations were not readable in their paper): we used ½ LOQ for samples below LOQ to present mean of all samples; [6] results from paired farm survey; [7] the author reported % positive samples and mean and median concentrations of all samples (organic and conventional); [8] mean is below LOD.

Results for DON, ZEA, and T-2/HT-2 from our analysis of data from field experiments and farm surveys are consistent with, and confirm, the results of a recent systematic review and meta-analysis of comparative (organic versus conventional) cereal grain and product composition data from all types of studies (controlled field experiment, farm survey, and retail survey) [46] (Figure 1), and an extensive retail survey which compared *Fusarium* mycotoxin contamination levels in common and spelt wheat flour brands available in Germany and the UK [50]. Specifically, both the unweighted and weighted meta-analysis found significantly lower ($p < 0.0001$) DON concentrations in organic cereal grain/products, and the unweighted meta-analysis (which allowed data from more studies to be included) also detected significantly lower concentrations of ZEA ($p = 0.0101$) and T-2/HT-2 ($p = 0.0351$) in organic cereal grain/products (Figure 1) [46]. Similarly, the wheat flour survey reported that DON concentrations were significantly lower ($p = 0.0060$) in organic wheat flour (49 ± 9 µg/kg dry weight) compared with conventional wheat flour (60 ± 6 µg/kg dry weight). Additionally, when whole-grain flour was compared, T-2/HT-2 concentrations were significantly lower ($p < 0.05$) in organic samples (1.46 ± 0.20 µg/kg dry weight) compared with conventional samples (2.74 ± 0.50 µg/kg dry weight) [50].

It is important to note that mycotoxin contamination levels reported in retail surveys of cereal products used for human consumption in Europe are usually substantially lower than those found in experimental studies and farm surveys carried out in the same countries [46,50]. This is mainly due to quality assurance systems used by grain storage and processing companies; QA systems involve testing of all batches (e.g., cereals harvested on specific fields by farmers) for mycotoxin contamination and only selecting batches for human consumption that have mycotoxin levels which are substantially lower than the maximum mycotoxin contamination levels set by the EU [26,50]. Additionally, the majority of cereal products consumed by humans in Europe is made from refined cereal flour, which is well documented to contain significantly lower mycotoxin levels than whole-grain flour [26,50].

3.1.1. Field Experiments

Replicated field experiments are designed to control a range of environmental and agronomic background conditions and thereby enable specific explanatory variables such as production system and specific agronomic practices to be investigated. However, given the known confounding effects of climatic/weather and other environmental background conditions on *Fusarium* infection and mycotoxin production, it is not possible to draw general conclusions from individual field experiments. It is therefore important to repeat experimental studies in different seasons and/or experimental sites with contrasting pedoclimatic conditions to allow interactions between the agronomic variables and environmental parameters to be identified. However, experimental trials are highly valuable to identify the cause–effect relationships as long as conclusions are limited to the individual or range of pedoclimatic background conditions in which experiments were performed. In this section, we summarise the results of experimental studies from different pedoclimatic regions.

Results from several field experiments suggest that *Fusarium* infection and mycotoxin concentrations may not be closely correlated. For example, a recent Polish study by Goral et al. [27] compared DON concentrations in 30 wheat cultivars grown in organic and conventional systems and reported significantly higher levels of *Fusarium* colonisation of kernels in an organic system, but no significant difference in DON concentrations. Taller cultivars had lower levels of FHB, and the authors reported that the same cultivars are often used in conventional and organic farming in Poland. They suggested that growing wheat under organic conditions reduces stress resulting from intensive mineral fertilisation and chemical crop protection in the fungus.

In a study carried out in Canada, Munger et al. [28] found significantly lower DON concentrations in organic wheat in a year with overall high DON contamination levels (2009), but no significant difference in the following year (2010) with overall moderate DON contamination levels. The authors suggested that high weed density in organic crops in 2009 may have had a protective effect against *Fusarium* infection/colonisation and that this may explain the lower DON concentration in organic wheat grain. It is interesting to note that in their study the DON producer *F. graminearum* was present at a significantly lower level in the no-tilled compared with ploughed organic system, while there was no effect on *F. graminearum* in the conventional system, and no effect of tillage on DON concentration in both organic and conventional grain.

Champeil et al. [32] reported results from a 3-year French field trial with wheat. Although they found lower *Fusarium* infection levels in organic wheat, they were unable to detect a consistent difference in DON contamination levels. In contrast, Birzele et al. [36], who carried out a 2-year field trial with wheat in Germany, reported a substantially lower occurrence of FHB and lower DON contamination of grain in organic compared with conventional farming plots.

There are a small number of studies which investigated the effects of a production system and selected specific agronomic parameters (e.g., fertilisation type and intensity) on FHB and/or mycotoxin contamination. Lacko-Bartošová and Kobida [29] reported a lower DON concentration in organic wheat but no significant effect of a production system on ZEA concentration in a study carried out in Slovakia. They also found that raising fertiliser input levels increased DON concentrations in both organic and conventional cereal production systems. In contrast, Hietaniemi et al. [37] found no significant effects of the production system and the N fertiliser input level on DON concentrations in oat grain produced in Finland.

Quaranta et al. [30] found significantly lower DON concentrations in organically compared with conventionally grown durum wheat in a 3-year trial, which was replicated in six locations in Southern and Central Italy. Similarly, a 3-year field trial in the Czech Republic, carried out by Vanova et al. [31], found lower DON concentrations in grain from organic compared with both low- and medium-intensity conventional systems. However, they detected no significant difference in grain DON levels between organic and high-intensity conventional systems.

As part of this review article, we also carried out statistical reanalyses of data from a 2-year Swiss field trial with wheat reported by Mäder et al. [34] and Griesshaber et al. [35]. This identified significantly lower concentrations of DON ($p = 0.02$) and HT-2 ($p = 0.01$) in organic (data from a biodynamic and a bioorganic system included in trials were pooled) systems compared with their conventional system. The mean concentrations of DON over

2 years in biodynamic, bioorganic, and conventional systems were, respectively, 36, 61, and 82 μg/kg, whereas concentrations of HT-2 were <1, 2 and 4 μg/kg, respectively [35]. These results suggest that there are positive associations between production intensity (e.g., input levels of total and/or water-soluble N with organic and/or mineral fertilisers) and grain mycotoxin levels. It is important to note that in the Swiss trial, the same crop rotation was used in all three systems, thus preventing confounding effects of rotation design.

Mäder et al. [34] also used wheat from their field trials in feed choice feeding trial with rats, which showed that the rats preferred organically to conventionally produced wheat. However, it should be pointed out that the preferences recorded may also have been due to differences in grain composition other than mycotoxin content between organic and conventional grain and that trial design did not allow the exact underlying reasons to be determined. The authors concluded that the higher nutritional quality of organic wheat grain is associated with the low agrochemical inputs used in organic farming and that there are strong positive associations between grain quality, low inputs of nonrenewable and/or scarce resources, and overall sustainability of grain production.

Schneweis et al. [33] carried out a 3-year trial in Germany with three wheat cultivars with a different susceptibility to *Fusarium* and reported in total lower concentrations of DON and ZEA in organically grown wheat grain; the mean DON and ZEA were 179 mg/kg and <5 mg/kg, respectively, in organic grain and 283 mg/kg and 28 mg/kg, respectively, in conventional grain. They also conducted a feeding trial with pigs and found slightly higher daily weight gain but lower carcass yield in pigs fed ad libitum with the organic wheat compared with pigs fed conventional wheat. As with the rat feeding trial in Switzerland [34], a higher weight gain may indicate improved palatability of organic wheat. The authors suggested that toxic effects of the higher mycotoxin levels in conventional wheat were unlikely because the DON and ZEA concentrations were all below an indicated health critical value, referring to 1000 μg/kg for DON [51]. This view is supported by the fact that the DON concentrations in pig diets were also below the known thresholds for the critical effects—reduced feed intake and weight gain—of DON in pigs published by EFSA [1]. The authors suggested that the difference in carcass yield may have been due to higher levels of crude fibre in the organic wheat.

3.1.2. Farm Surveys

Farm surveys, which compared *Fusarium* infection and mycotoxin levels from organically and conventionally managed farms, can also provide valuable information, but it is important to point out that pedoclimatic conditions and agronomic protocols may differ between both conventional and organic farms—even when farms in the same geographical region are compared. It is therefore important to consider that these differences may increase the variability of results and are confounding factors in farm-survey-based studies. Due to these confounding effects, it is difficult to extrapolate cause–effect relationships from survey data. However, well-designed farm surveys which collect samples and data on a large number of farms and in several seasons can provide better estimates of the overall impact of production systems and specific agronomic parameters on *Fusarium* infection and mycotoxin loads than field experiments. In this section, therefore, the results from larger well-designed farm surveys are summarised.

A recent study by Polisenská et al. [38] in the Czech Republic reported data from two survey approaches that compared DON and ZEA in organic and conventional wheat in three consecutive wheat harvest years. Approach 1 was to randomly sample wheat in fields from organic and conventional farms within representative areas. Approach 2 was to collect paired samples of wheat grown after the same preceding crops (to minimise potential confounding effects of rotation design) from neighbouring organic and conventional farms within the same regions also used for approach 1. Approach 1 found significantly lower DON concentrations and a trend towards lower ZEA concentrations (p = 0.051) in organic wheat. However, although DON levels were numerically higher, no significant differences were detected with survey approach 2. Based on these findings, the authors suggested that rotation design is a major agronomic factor responsible for the differences in mycotoxin loads between organic and conventional production systems and that the more widespread use of maize as a preceding crop in conventional production may have been a major driver for high mycotoxin loads in conventional systems observed when sampling method 1 was used. However, the higher number of samples collected, and thus the higher statistical power, when survey approach 1 was used may have also contributed to the different results obtained with the two contrasting survey approaches.

Bernhoft et al. [7,40] in a study carried out in Norway also used a paired farm sampling approach when comparing *Fusarium* infestation and mycotoxins in organic and conventional wheat, oats, and barley grain samples in a 3-year survey which also recorded a range of specific agronomic parameters on organic and conventional farms. Since weather conditions during the growing season are known to have a large effect on *Fusarium* infection and mycotoxin contamination levels in cereals, each pair of cereal samples was collected in geographical proximity and at a similar harvest time. The level of *Fusarium* infestation was slightly but significantly lower in organic wheat, oat, and barley grain samples. DON concentrations were significantly lower in wheat. There was a trend towards lower DON concentrations in organic oats ($p = 0.056$), while levels were similar in organic and conventional barley samples. HT-2/T-2 concentrations were significantly lower in organic oats and barley samples, while none of the organic and conventional wheat samples tested positive for HT-2 or T-2. ZEA levels could not be compared since concentrations were below the limit of detection in most organic and conventional samples. When potential effects of specific agronomic parameters were studied in Norway, rotation/preceding crop was identified as a significant factor affecting both DON and HT-2 contamination levels [7]. Specifically, cereal as a precrop was associated with higher mycotoxin loads than noncereal crops. However, it should be pointed out that maize, which has frequently been reported to increase *Fusarium* infection and mycotoxin levels [52], was not used in the Norwegian cereal production when the surveys were carried out, and that the effects observed were linked to small-grain cereal preceding crops [7].

Schöneberg et al. [13] in Switzerland surveyed *Fusarium* infection and mycotoxin contamination in barley for 2 years and collected information on specific agronomic practices used on the farms included in the survey. Their study found lower infection levels of the DON producer *F. graminearum* and lower DON concentrations in grain from organic farms. They also reported that both DON and *Fusarium* infection levels increased with increasing nitrogen (N) fertilisation, with the use of fungicides, with maize as the preceding crop and with reduced tillage systems on farms.

An extensive survey-based study by Edwards [41,45,48] compared *Fusarium* mycotoxins in organic and conventional wheat, oats, and barley over 5 years (2001–2005) in the UK. He reported no significant differences in DON concentrations between organic and conventional wheat and barley and no significant differences between systems for ZEA concentrations in wheat and for HT-2 concentrations in barley. However, organic wheat and oats were found to have significantly lower concentrations of HT-2/T-2.

In contrast, an extensive 8-year farm survey by Meister [42] in Germany reported lower DON and ZEA concentrations in organic wheat and rye. However, it should be noted that ZEA was only detected in a small number of rye samples and was therefore not included our calculations of average mean mycotoxin concentration (Tables 1 and 2). Lower concentrations of both DON and ZEA in organic wheat were also found in a 2-year Belgian survey by Pussemier et al. [24]. Furthermore, a 1-year survey by Döll et al. [43] in Germany reported lower DON concentrations in organically produced wheat. Döll et al. also reported trends towards lower ZEA levels in wheat and DON levels in rye, but these results were not included in our review due to the low number of comparable samples assessed in this study.

Another survey carried out in Germany by Gottschalk et al. [49] compared T-2 and HT-2 and other type A trichothecenes in oats and also reported lower concentrations in the organic produce. Recently, a survey on mycotoxins in oats in Ireland by Kolawole et al.

primarily detected T-2 and HT-2 and reported a significantly lower prevalence of these toxins in the organic grain and significantly lower concentrations of T-2 in organic grain when concentrations in samples with concentrations above the limit of quantification (LOQ) were compared [47]. Our reanalysis of their data (which involved estimating concentrations in samples below the LOQ as ½ LOQ) showed that the mean T-2+HT-2 concentrations in conventional oat samples were significantly (2.9 times) higher than those found in organic oat samples.

A 2-year survey of durum wheat (*Triticum durum*) grain produced in Spain by Giménez et al. also reported trends towards significantly lower concentrations of DON in organic wheat [39]. They concluded that organic production may provide some reduction in DON concentrations, which could be due to the lower intensity of cultivation and to difference in crop rotation design.

Different to the survey-based studies described above, a 1-year survey by Marx et al. [44] carried out in Germany reported no effect of the production system on DON concentrations in wheat, but increased concentrations of DON in organic rye and of ZEA in organic wheat grain.

Overall, the evidence from farm surveys is consistent with the results from replicated field experiments (see Section 3.1.1 above). However, it is important to note that many of the surveys and field experiment studies conducted over more than 1 year detected significant differences in overall mycotoxin levels and the relative difference in mycotoxin levels between organic and convention cereal grain between years, which confirm that weather conditions during the growing season are a strong driver for mycotoxin contamination levels. However, most studies were not designed to accurately estimate variation in mycotoxins associated with (i) environmental factors versus (ii) contrasting agronomic practices. One exception is the extensive study by Munger et al. [28], which suggests that relative differences in mycotoxin levels between production systems are more distinct in seasons or locations with conditions that generate high *Fusarium* infection pressure.

3.2. Studies That Investigated Effects of Specific Agronomic Practices on Mycotoxin Levels

As described above, organic and conventional cereal production protocols differ in a range of agronomic parameters, including rotation design, crop protection methods, and fertiliser types and input levels used. A large number of studies have investigated the effects of these agronomic practices on *Fusarium* infection and mycotoxin levels [10,15]. Although these studies were mainly carried out within the context of conventional production protocols, they do provide important information about the potential agronomic parameters responsible for difference in mycotoxin contamination in cereal grain from organic and conventional production systems and help to explain the variation between comparative studies (see Sections 3.1.1 and 3.1.2 above).

The most important agronomic variables that were shown to affect *Fusarium* infection and mycotoxin contamination are therefore summarised in separate sections below. Specifically, we describe information on the effects of crop rotation design, N fertilisation, use of fungicides and herbicides, and tillage on *Fusarium* infestation/infection and mycotoxin contamination, since organic and conventional systems differ considerably in these parameters (see Sections 3.2.1–3.2.4 above). We also summarise results of studies which investigated the effect of variety choice/crop resistance, soil carbon levels, soil and aboveground microbiota, and biological control agents on mycotoxin levels (Sections 3.2.5–3.2.8).

It is important to point out that different to the well-known climatic and weather drivers for mycotoxin contamination, farmers are in control of their agronomic protocols and can change to alternative practices if they are shown to reduce the risk of mycotoxin contamination.

3.2.1. Crop Rotation

A wide range of studies have shown that using diverse crop rotations in which non-*Fusarium* host plant species precede cereal crops is an effective way of reducing the risk of

Fusarium and mycotoxin contamination in cereal grains [4,6,7,10,13–15,47,52–63]. Growing non-*Fusarium* host crops (e.g., oilseed rape, potatoes, legumes, and field vegetables) before cereals reduces the level of *Fusarium*-infected crop debris, and after 2–3 years of growing a non-*Fusarium* host plant species, they are thought to effectively remove *Fusarium* pathogen inoculum from agricultural soils. Most studies that investigated the effects of preceding crops on mycotoxin levels assessed only DON, but studies that assessed ZEA and/or T-2/HT-2 levels reported that growing non-*Fusarium* host crops before cereals also reduced ZEA [62] or T-2/HT-2 [7,14,47,60] levels in cereal grains. One study reported that growing non-*Fusarium* hosts before cereals resulted in both (i) lower *F. graminearum* infestation and DON levels and (ii) lower *F. langsethiae* infestation and lower T-2/HT-2 levels [7].

Intercropping cereals with non-*Fusarium* host plant species was also shown to reduce *Fusarium* mycotoxin levels in cereals [64].

Particularly, a high incidence of FHB and increases in DON concentrations in harvested grain are often observed if small grain cereal crops are planted after maize [52,55]. For example, planting wheat after crops other than maize was found to lower the DON content by on average 33% [52].

3.2.2. Mineral Nitrogen Fertiliser

There is now substantial evidence that the increasing use of mineral N fertilisers, which was introduced during the green revolution to improve grain yields and protein concentrations in cereals, has also increased the incidence and severity of a range of biotrophic crop diseases, including powdery mildew, rusts, and *Fusarium* spp. [65]. However, it should be pointed out that the relationships between fertiliser use and *Fusarium* infection and mycotoxin levels in cereal grains are complex and shown to be influenced by the type, levels, and timing of using fertilisers, other agronomic factors, and pedoclimatic background conditions [58].

Lemmens et al. [66] in Austria showed that different types of N fertilisers, both organic (colza cake, animal tankage, or molasses) and mineral (ammonium–nitrate–urea or nitramoncal), similarly increased FHB in wheat in a dose-dependent manner from 0 to 160 kg N/ha. They also reported that FHB and DON levels in wheat cultivars artificially inoculated with *F. graminearum* and *F. culmorum* increased with increasing N input levels up to an input level of 80 kg N/ha, but remained similar to those observed at 80 kg N/ha at higher N input levels. Similar effects of N fertilisation were also reported in wheat by Heier et al. [67] in Germany and in wheat and barley by Martin et al. [68] in Canada.

Yi et al. [69] in Germany reported lower FHB severity when wheat was mainly fertilised with nitrolime (calcium cyanamide) when compared with ammonium nitrate at the same total N input level. They suggested that this was due to the slower release and more gradual availability of N to plants when nitrolime was used as fertiliser. Similar results were presented by Teich [70] in Canada, who reported lower FHB levels with urea compared with ammonium nitrate as N fertiliser. Van der Burgt et al. [71] in the Netherlands studied FHB and DON contamination in wheat by using different organic fertilisers and described a positive association between N input levels and DON concentrations in grain. They suggested that the high N input levels increase mycotoxin contamination by generating a denser crop canopy with a microclimate that favours DON-producing *Fusarium* species. Lacko-Bartošová and Kobida [29] in Slovakia found that the use of both high inputs of manure and synthetic N fertiliser increases DON concentrations. Similarly, Schöneberg et al. [13] reported increased DON concentrations with increased N fertilisation in barley, and Bernhoft et al. [7] in Norway reported that the use of mineral fertilisers significantly increased *Fusarium* infestation levels in kernels of wheat, oats, and barley.

In contrast, studies by Hietaniemi et al. [37] in Finland and Pageau et al. [54] in Canada detected no significant effects of N fertiliser input levels on DON levels in oats and barley, respectively. A range of other studies also reported either no significant effects or inconsistent results when FHB or DON concentrations in wheat grown with different N fertiliser types or N input levels were compared [53,63,72–74]. Hofer et al. [75] in Germany observed no significant effect of N fertilisation on FHB in barley under natural pathogen pressure, but decreased *Fusarium* and DON contaminations with increased N after artificial infection with selected *Fusarium* species. Additionally, a study by Yang et al. [76] in Denmark found that low N application rates result in increased *Fusarium* infection in barley and suggested higher N fertiliser inputs as a potential strategy to minimise FHB in barley.

The complex relationship between fertilisation regimes and *Fusarium* incidence and severity in cereals was also discussed by Champeil et al. [56]. They suggested that the variability observed for effects of N fertilisation between studies may have been due to differences in the ratios of different mineral nutrients being available to crops or indirect effects of N fertilisation on soil biological parameters (e.g., the use of organic fertilisers was associated with improved soil biological activity and both carbon and N content), whereas mineral fertilisation may have a negative impact on the soil microbiota [77–79]. Furthermore, there is evidence that excessive N fertilisation or availability may alter cell wall morphology and chemical composition [80] and reduce phenolic/antioxidant concentrations and the resistance of cereal crops against certain biotrophic pathogens (powdery mildew, rust) in wheat [22].

3.2.3. Fungicides and Herbicides

Studies aimed at developing/assessing fungicide treatments to prevent FHB and mycotoxin contamination in conventional cereal production have reported variable, inconsistent, and sometimes contrasting results, and there are currently no fungicides that can provide satisfactory control of FHB, especially in seasons with high *Fusarium* infection pressure [10,15].

Azole fungicides, which are widely used for powdery mildew control in cereals, were reported to also reduce FHB and mycotoxin contamination, but overall, the levels of reduction achieved were found to be unsatisfactory for commercial production. For example, studies in Germany and USA showed that, even when optimum application dates, levels, and combinations of triazoles were used, FHB and DON levels could only be reduced by around 50% [52,81]. A study in Canada showed that multiple applications of azole fungicides may further reduce FHB, but the costs of such treatments are prohibitive for commercial cereal production [82]. Experimental studies in Italy showed that triazole application prior to artificial inoculation of crops with *Fusarium* will reduce FHB and DON levels [83], but these results lack practical relevance. An experiment that evaluated the effects of prothioconazole applications in wheat in England reported a significant reduction of DON levels but inconsistent effects for ZEN levels [84]. It is important to note that the susceptibility to azole fungicides differ between *Fusarium* species [85], and that repeated use of these fungicides increases the risk of development of azole-resistant *Fusarium* species [86].

Strobilurin fungicides (e.g., azoxystrobin), which are used to control diseases such as powdery mildew and rusts in cereals, were shown to have no direct effect on *Fusarium* species [87–89]. However, by inhibiting the colonisation of cereal plants by commensal or other pathogenic fungal species, they may increase FHB and mycotoxin levels [87,88].

Several field experimental studies found that infection by *F. langsethiae* concentrations of T-2 and HT-2 mycotoxins produced by this *Fusarium* species cannot be reduced by any commonly used fungicides [4,90]. However, by reducing competition from other commensal or pathogenic fungal species, fungicide treatments may increase *F. langsethiae* infection and T-2/HT-2 contamination. These results were recently confirmed by Karron et al. [91] in Estonia, who reported that fungicide treatments did not effectively reduce DON and T-2/HT-2 levels in barley.

The effects of herbicides, especially glyphosate, on *Fusarium* infestation and mycotoxin production have also been reported. The first reports that glyphosate increases the incidence of infections from *Fusarium* and certain other soil-borne pathogens were made more than 30 years ago by Altman (USA) and Rovira (Australia) [92]. Later, Fernandez et al. [93] summarised a set of comprehensive Canadian studies into the effect of glyphosate on

Fusarium infection levels in wheat and barley crops. They reported that glyphosate treatment was consistently associated with higher FHB, primarily due to *F. graminearum* and *F. avenaceum*. They suggested that the herbicide might induce changes in fungal community structure via a range of potential mechanisms, including (i) inducing stimulation of *Fusarium* colonisation, (ii) inhibition of other commensal or pathogenic fungi, and (iii) inhibition of plant resistance responses.

More recently, Martinez et al. [94] reviewed the evidence for negative impacts of glyphosate-based herbicides on disease resistance and crop health. They concluded that the currently available evidence does not confirm the assumption that glyphosate-based herbicides have no negative effects on plant health when applied according to the manufacturers' recommendations. In contrast, they suggested that glyphosate-based herbicides potentially enhance the virulence of phytopathogenic microbial species, such as *Fusarium*. In this context, it is important to note that glyphosate applied to previous crops and adsorbed to soil particles was recently shown to be released and cause phytotoxicity when phosphate fertilisers are applied prior to planting crops [95].

3.2.4. Tillage

There is substantial evidence that deep tillage, and especially inversion ploughing, is an effective preventative strategy to reduce *Fusarium* infection and production of mycotoxins in cereals, since tillage incorporates cereal stubbles and crop residues left on the soil surface during harvest, which are the major *Fusarium* inoculum source, into the soil [15,28,52,53,55,57,58,62,96–98].

However, it is important to note that high *Fusarium* inoculum levels in soil do not necessarily lead to high crop infestation. Results from several studies suggest high levels of disease suppressiveness in soils, which is often associated with high soil biological activity or antagonistic soil microbial communities that may also reduce *Fusarium* inoculum and disease development [10,58,99]. This may explain why some studies did not detect significant reductions of *Fusarium* and mycotoxins in cereals following deep tillage [10,28,53,98], in particular, studies investigating organic/low input production [28,58,100]. These results may indicate that tillage is less important for *Fusarium* control in soils with robust and balanced biotic and abiotic factors that result in high disease suppressiveness.

3.2.5. Regenerative Agricultural Practices and Soil Organic Matter

Some soil parameters, such as a high clay and/or organic matter content, were also linked to a reduced risk of *Fusarium* infection [99,101–103]. One proposed explanation for this observation is that clay and organic-matter-rich soils provide more favourable conditions for high microbial activity and population density of antagonistic microorganisms (see also Section 3.2.7 below).

There is currently a growing interest in regenerative agricultural practices, which aim at building up soil organic matter, physical stability, biological activity, and inherent fertility (unit crop yield achieved per unit fertiliser input) as a sustainable alternative to an intensive (high input–high output) and monoculture-/short-rotation-based agricultural system. One of the benefits of regenerative agriculture may well be that it will reduce the overall risk of *Fusarium* and mycotoxin contamination in cereal production, and this hypothesis should be investigated further in future studies.

3.2.6. Genetic Resistance

There has been considerable effort to breed and select cereal cultivars with high levels of *Fusarium* resistance, and it is well known that there is considerable variation in sensitivity to *Fusarium* both between species and between cultivars/varieties of small cereal genera (wheat, barley, oats, rye). This has been reviewed in detail previously and is therefore not described in detail in this review (e.g., [104]). However, it is important to point out that these reviews concluded that there are currently no completely FHB-resistant cultivars of wheat, barley, oats, and rye [10,15] and that there is continuing effort to breed for FHB resistance especially in wheat in regions with high *Fusarium* disease levels or where *Fusarium* pressure is predicted to increase due to an increase in maize production or climate change [104,105].

Furthermore, while some studies reported correlations between FHB and DON contamination, others did not. For example, Bissonnette et al. [106] found correlations between levels of FHB and DON concentrations and concluded that 'selection of a moderately resistant cultivar provides effective control of DON accumulation in the grain and mycotoxin accumulation in the stem'. In contrast, Ji et al. [107] reported a lack of correlation between FHB and DON contamination levels for wheat cultivars with different degrees of FHB resistance. The reasons for these variable results are poorly understood but may be linked to differences in environmental background conditions, contrasting agronomic practices used in trials and plant physiological factors that induce stress in the fungus or prevent toxin production [108].

It is well documented that there is a positive correlation between plant height/stem length and FHB resistance in wheat, and several QTLs for FHB resistance identified in wheat were shown to increase stem length [104,109]. The effect of stem/straw length on FHB may also affect *Fusarium* mycotoxin levels and is thought to be due to several factors (see Buerstmayr et al. [104] for a detailed description of the physiological parameters linked to *Fusarium* resistance in wheat). Most importantly, crop debris on the soil surface are the main primary *Fusarium* inoculum source for infection in the next wheat growing season. Since spores produced on soil surface residues need to reach the heads of wheat plants for successful grain infection, shorter plants are known to be more at risk from infection by rain-splash-dispersed conidia or ascospores [110]. However, greater *Fusarium* resistance in taller cultivars was also found with artificial spore inoculation of crops, which suggests that other mechanisms may also contribute. For example, a taller wheat variety developed for the organic sector was recently described to express higher levels of rust and *Septoria* resistance and phenolics (which are known to contribute to foliar disease resistance) in wheat leaves than a short-straw variety developed for the conventional sector [22]. Additionally, plant height may increase air circulation and reduce humidity and periods of leaf wetness in the crop canopy and thereby generate less favourable environmental conditions for infection of florets and grain [104].

In this context, it is important to note, that breeding of modern wheat varieties over the last 60 years focused on the introduction of semidwarfing genes and the selection for shorter stem length to (i) reduce the risk of lodging (which increases *Fusarium* infection risk due to plants being closer to or touching the soil surface) and (ii) increase harvest index and maximum yield potential in high-input conventional farming systems [22,104]. QTLs for *Fusarium* resistances that increase stem length are therefore, to our knowledge, not exploited to increase FHB resistance in wheat breeding programmes for the conventional sector in Europe.

In contrast, organic farmers often choose traditional longer-straw wheat varieties and, more recently, varieties from organic-farming-focused breeding programmes, which also tend to have longer stems/straw than modern varieties developed for the conventional sector [22,80]. This is mainly because (i) longer straw varieties are thought to suppress weeds more efficiently, (ii) the use of manure instead of mineral N fertiliser results in a lower risk of lodging, and (iii) there is also a correlation between positive straw length and protein content in wheat, and this may compensate for the inability to increase protein content via late mineral N applications in organic farming [22,111]. The use of longer-straw varieties in organic farming systems may therefore also contribute to lower mycotoxin levels in organic wheat grain. However, in seasons with high levels of lodging in cereals, the use of long-straw varieties may increase *Fusarium* infection and grain mycotoxin levels in organic crops, which may contribute to explaining the variability between seasons and/or studies that compared grain mycotoxin levels in organic and conventional crops.

In this context, it is important to consider the results of a study by Góral et al. [27], who compared mycotoxin contamination in factorial field experiments with 30 wheat cultivars that were grown in organic and conventional production systems. They found higher levels of the DON-producing *Fusarium* species *F. graminearum*, and of *F. poae*, *F. sporotrichioides*, and *F. avenaceum* in the organically produced kernels. However, concentrations of DON and other trichothecenes were not significantly different or lower in organic compared with conventional wheat kernels. Whether this was linked to a difference in gene expression/physiological parameters in the crop plant and/or on the fungus (e.g., stress caused by fungicide applications in conventional crops) resulting from contrasting agronomic practices is not understood.

3.2.7. Soil and Plant Microbiota

An active soil microbiota including bacteria, fungi, and protists plays an important role for various soil-based ecosystem services, including nutrient cycling and pest and disease regulation [112,113]. Furthermore, both targeted and untargeted management of soil and plant microbial communities appear to be promising in the sustainable improvement of food crop yield and the nutritional quality and safety of crops [114]. Several studies have reported a positive effect of organic farming on soil health and quality, including microbial activity and community diversity. In their global metastudy, Lori et al. [112] quantified differences in key indicators for soil microbial abundance and activity in organic and conventional cropping systems. They found that organic systems had 32% to 84% greater microbial biomass of C and N, total phospholipid fatty acids, and enzyme activities related to C and N cycling, showing that overall organic farming enhances total microbial abundance and activity in agricultural soils. These differences may result from a range of agronomic factors, including contrasting crop rotations, tillage systems, fertilisation regimes, and/or crop protection protocols used in organic and conventional farming, although the exact contribution of individual agronomic parameters to soil biological/microbial activity is unknown. It is therefore currently difficult to assess to what extent the effect of specific agronomic practices used in organic farming on FHB and mycotoxin levels was due to their impact on soil biological/microbial activity/diversity.

Karlsson et al. [115] compared fungal diversity in the phyllosphere of wheat plants grown in organic and conventional farming systems in Sweden, and they found higher richness of fungal taxa in organic wheat. As with microbial richness below the ground, they suggested that higher microbial richness aboveground may be linked to improved plant health and productivity. The same research group also investigated the effects of fungicide applications on fungal community composition in the wheat phyllosphere [116]. They found moderate but significant effects of several commonly used fungicides on the relative abundance of several saprotrophic fungi, but no significant effect on specific fungal pathogens of wheat. They also reported that production intensity in conventional systems, measured as the number of pesticide applications and the amount of N fertiliser applied, had a significant effect on *Fusarium* community composition in wheat, but found no significant difference between organic and conventional systems [117]. Karlsson et al. [118] recently published a review paper on the interactions between the host commensal microbiota and the pathogenic microbiota and their potential effects on the development of cereal FHB and mycotoxin production by *Fusarium* species, which provides more detailed information.

3.2.8. Biological Control Agents and Botanical Fungicides

In line with knowledge on the important role of the soil and plant microbiota for plant health and productivity are biological control approaches to pest and disease management. Various organisms, such as yeasts, bacteria, and nonpathogenic and/or non-mycotoxin-producing fungal strains, have been reported to reduce mycotoxin accumulation in crops, including cereals, and their effects are thought to be due to a range of mechanisms, including direct competition with the toxin-producing microorganisms [10,15,119]. Furthermore, a range of natural fungicides based on plant extracts (e.g., phenolic compounds and essential oils extracted from plants) have been suggested as promising substitutes for synthetic fungicides [10,15]. However, there is limited information on the effect of antagonistic microorganisms and botanical fungicides on *Fusarium* infection and mycotoxin level in cereals.

4. Conclusions

Our review of studies that compared the *Fusarium* mycotoxins DON, ZEA, and T-2+HT-2 levels in organic and conventional cereal grains, wheat, oats, barley, and rye shows that the majority of scientific studies considered to be of high quality reported lower mycotoxin levels in organic production, while nearly all of the remaining studies reported no significant difference between the two systems. Specifically, our review found that 24 comparisons in high-quality publications reported lower mycotoxin levels in organic production, 16 found no significant difference, and only 2 reported higher mycotoxin levels in organic production.

Our analyses of studies that investigated the effects of specific agronomic parameters on FHB and/or mycotoxin contamination risk suggest that (i) diverse crop rotations, (ii) agronomic strategies that elevate soil organic matter, and microbial/biological activity levels are associated with lower *Fusarium* mycotoxin concentrations, whereas high mineral nitrogen fertiliser inputs and the use of certain fungicides and herbicides may increase the risks of *Fusarium* mycotoxin levels in cereals. These agronomic parameters may also be important explanatory variables for the lower mycotoxin levels recorded in organic systems in comparative studies, but this would have to be confirmed in well-designed factorial field experiments and/or farm surveys in the future.

This review was designed to provide a qualitative overview of the available evidence on *Fusarium* mycotoxin levels in organic and conventional cereal production and the potential explanatory variables responsible for differences between production systems. The authors feel that it is important to carry out detailed quantitative comparisons based on meta-analysis of all available scientifically sound data in the future.

Our review provides evidence that organic cereal production is a holistic approach to reduce *Fusarium* mycotoxin loads in cereal crops, which is in line with several of the 17 Sustainable Development Goals by the United Nations, in particular, goal 2 (promote sustainable agriculture), goal 3 (ensure healthy lives (e.g., by reducing death and diseases caused by dangerous chemicals and toxins)), goal 6 (improve water quality (e.g., by preventing pollution of freshwater ecosystems with poisoning from dangerous chemicals and materials)), goal 12 (promote responsible production), goal 13 (take climate action), and goal 15 (take care of life on land).

Author Contributions: Conceptualisation, A.B. and C.L.; methodology, A.B.; software, A.B.; validation, A.B. and C.L.; formal analysis, A.B. and J.W.; investigation, A.B. and J.W.; resources, A.B., C.L. and J.W.; data curation, A.B. and J.W.; writing—original draft preparation, A.B.; writing—review and editing, A.B., J.W. and C.L.; visualisation, A.B. and C.L.; supervision, A.B.; project administration, A.B.; funding acquisition, A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data will be made available upon reasonable request to author A.B.

Acknowledgments: The Norwegian Veterinary Institute is acknowledged for letting A.B. spend working time to generate the manuscript. The support from Catherine Leifert for proofreading the manuscript is gratefully acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

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