

Review

# ***Alternaria* Mycotoxins in Wheat: A Review of Their Occurrence and Significance**

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**Abstract:** Wheat (*Triticum aestivum* L.) is one of the most important cereal crops worldwide and represents a major component of human and animal nutrition. However, wheat grains are susceptible to contamination by various fungal species capable of producing toxic secondary metabolites known as mycotoxins. Among these contaminants, *Alternaria* mycotoxins have gained increasing attention due to their widespread occurrence in cereals and their potential implications for food safety. Species belonging to the genus *Alternaria*, particularly *Alternaria alternata*, *A. tenuissima*, and *A. infectoria*, are commonly associated with wheat production and are capable of producing several biologically active metabolites, including alternariol (AOH), alternariol monomethyl ether (AME), tenuazonic acid (TeA), tentoxin (TEN), and altenuene (ALT). The aim of this review was to summarize current knowledge regarding the occurrence, toxicological significance, and food safety implications of *Alternaria* mycotoxins in wheat. Available studies indicate that contamination of wheat with *Alternaria* toxins is a global phenomenon, with TeA, AOH, and AME being the most frequently detected compounds. The occurrence and concentration of these toxins are influenced by numerous factors, including climatic conditions, geographical location, agronomic practices, fungal species composition, and post-harvest handling. Recent findings suggest that climate change may further contribute to the prevalence and distribution of *Alternaria* species and their associated toxins. Toxicological investigations have demonstrated that several *Alternaria* metabolites possess cytotoxic, genotoxic, mutagenic, and potentially carcinogenic properties. In particular, AOH and AME have been identified as compounds of concern due to their ability to induce DNA damage and oxidative stress. Nevertheless, important knowledge gaps remain regarding chronic dietary exposure, mixture toxicity, and long-term health effects. Furthermore, the lack of harmonized regulatory limits for most *Alternaria* toxins represents a significant challenge for food safety management. Overall, the available evidence indicates that *Alternaria* mycotoxins constitute an emerging food safety concern in wheat production systems. Continued monitoring, improved analytical methodologies, comprehensive toxicological studies, and multidisciplinary research efforts are essential for enhancing risk assessment and supporting the development of effective regulatory and mitigation strategies.

**Keywords:** *Alternaria* mycotoxins; wheat; alternariol; alternariol monomethyl ether; tenuazonic acid; food safety; occurrence; toxicology.

## 1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops worldwide and represents a staple food for a large proportion of the global population. Due to its nutritional value and widespread use in human and animal nutrition, maintaining the quality and safety of wheat grains is of great importance. However, wheat production is frequently challenged by various biotic and abiotic factors, among which fungal contamination and the associated production of mycotoxins are considered major concerns for food safety and agricultural sustainability [1].

Mycotoxins are secondary metabolites produced by several fungal genera, including *Aspergillus*, *Penicillium*, *Fusarium*, and *Alternaria*. While considerable attention has traditionally been focused on aflatoxins, ochratoxins, and *Fusarium* toxins, increasing evidence indicates that toxins produced by fungi belonging to the genus *Alternaria* may also pose significant risks to food and feed safety. Species of *Alternaria* are ubiquitous plant pathogens and saprophytes capable of infecting a wide range of agricultural commodities, including cereals, fruits, vegetables, and oilseeds. Among cereal crops, wheat is particularly susceptible to contamination by various *Alternaria* species during cultivation, harvest, and storage [2–7].

Several *Alternaria* species are capable of producing a diverse range of toxic metabolites, commonly referred to as *Alternaria* mycotoxins. The most frequently reported compounds include alternariol (AOH), alternariol monomethyl ether (AME), tenuazonic acid (TeA), tentoxin (TEN), and altenuene (ALT). These toxins have attracted growing scientific interest due to their widespread occurrence in food commodities and their potential adverse effects on human and animal health. Toxicological studies have demonstrated that certain *Alternaria* toxins exhibit cytotoxic, genotoxic, mutagenic, and potentially carcinogenic properties, raising concerns regarding chronic dietary exposure [4–8].

The occurrence of *Alternaria* mycotoxins in wheat is influenced by numerous factors, including environmental conditions, agronomic practices, geographical location, fungal species composition, and post-harvest handling. Climate change, characterized by increasing temperatures and altered precipitation patterns, may further contribute to the prevalence and distribution of *Alternaria* species and their associated toxins. Consequently, monitoring the occurrence of these contaminants has become increasingly important for ensuring food safety and protecting public health [9–11].

Despite the growing number of studies investigating *Alternaria* mycotoxins in cereals, significant knowledge gaps remain regarding their occurrence, toxicological significance, and regulatory management. Furthermore, unlike several well-established mycotoxins, regulatory limits for most *Alternaria* toxins have not yet been widely established, highlighting the need for continued research and risk assessment [4,7,12].

Therefore, the aim of this review is to provide an overview of the major *Alternaria* mycotoxins, summarize current knowledge regarding their occurrence in wheat, discuss their toxicological significance and food safety implications, and highlight current challenges and future perspectives related to their monitoring and control [4,7,9].

## 2. *Alternaria* fungi and their major mycotoxins

The genus *Alternaria* comprises a diverse group of filamentous fungi that are widely distributed in nature and commonly associated with plants, soil, air, and agricultural commodities. Members of this genus are recognized as important plant pathogens, causing a variety of diseases in numerous crops, including cereals, fruits, vegetables, and oilseed plants. In wheat production systems, *Alternaria* species may colonize grains before harvest, during maturation, and under unfavorable storage conditions, thereby contributing to quality deterioration and mycotoxin contamination [5,6,9,13].

Among the numerous species identified within the genus, *Alternaria alternata*, *Alternaria tenuissima*, and *Alternaria infectoria* are most frequently associated with wheat grains and cereal-based products. These fungi are capable of producing a broad spectrum of secondary metabolites with varying biological activities and toxicological properties. The production of mycotoxins depends on

several factors, including fungal strain, substrate composition, temperature, water activity, and environmental conditions [10,13,14]. The most important *Alternaria* mycotoxins detected in wheat and wheat-derived products include alternariol (AOH), alternariol monomethyl ether (AME), tenuazonic acid (TeA), tentoxin (TEN), and altenuene (ALT). Among these compounds, AOH and AME are dibenzo- $\alpha$ -pyrone derivatives that have attracted significant attention due to their genotoxic and mutagenic potential. Experimental studies have demonstrated that both toxins can induce DNA damage and oxidative stress in mammalian cells, raising concerns regarding long-term dietary exposure [5,7,15–18]. Tenuazonic acid (TeA) is generally considered the most frequently occurring *Alternaria* toxin in cereal grains and often occurs at higher concentrations than other toxins. It is known to inhibit protein synthesis and has been associated with acute toxic effects in various biological systems. Tentoxin (TEN), a cyclic tetrapeptide, is primarily recognized for its phytotoxic activity, while altenuene (ALT) is commonly detected alongside other *Alternaria* metabolites and may contribute to the overall toxicological burden of contaminated commodities [19,20].

In recent years, increasing attention has also been directed toward the co-occurrence of multiple *Alternaria* toxins in the same sample. Simultaneous contamination may result in additive or synergistic toxic effects, although the mechanisms and health implications of such interactions remain insufficiently understood. Consequently, comprehensive monitoring of *Alternaria* mycotoxins has become an important component of food safety assessments, particularly in cereal crops such as wheat [21–23].

### 3. Occurrence of *Alternaria* mycotoxins in wheat worldwide

The occurrence of *Alternaria* mycotoxins in wheat has received increasing scientific attention over the last decade due to growing concerns regarding food safety and consumer health. Numerous studies conducted worldwide have confirmed the presence of *Alternaria* toxins in wheat grains and wheat-based products, indicating that contamination is a widespread phenomenon rather than a geographically restricted issue. The prevalence and concentration of these toxins are influenced by environmental conditions, agricultural practices, fungal species composition, and post-harvest handling procedures (Table 1). [21–29]

**Table 1.** Summary of the occurrence of major *Alternaria* mycotoxins in wheat worldwide.

Region	Most Frequently Detected Toxins	Main Findings
Europe	TeA, AOH, AME	Frequent contamination reported in wheat grains and flour Frequent contamination reported in wheat grains and flour [21,22,25–27].
Asia	TeA, AOH, TEN	High prevalence associated with warm and humid conditions High prevalence associated with warm and humid conditions [23,24,28].
North America	TeA, AOH	Moderate occurrence in wheat and wheat-derived products Occurrence reported in wheat-based products and monitoring surveys [4,27].
South America	AOH, AME, TeA	Regular detection in wheat-growing regions Regular detection in wheat-growing regions and cereals [9].
Australia	TeA, AME	Occasional contamination linked to climatic conditions Occasional contamination linked to climatic conditions and cereal monitoring [9].

TeA – tenuazonic acid; AOH – alternariol; AME – alternariol monomethyl ether; TEN – tentoxin.

Among the various *Alternaria* toxins, tenuazonic acid (TeA) is generally reported as the most prevalent and abundant compound in wheat. Alternariol (AOH) and alternariol monomethyl ether (AME) are also frequently detected, while tentoxin (TEN) and altenuene (ALT) are usually found at lower concentrations (Table 2). The simultaneous occurrence of multiple toxins in a single sample is commonly reported, highlighting the complexity of *Alternaria* contamination and the potential for combined toxicological effects [22–26].

Studies conducted in European countries have demonstrated considerable variability in contamination levels. Investigations performed in Italy, Germany, Croatia, and Serbia have revealed frequent contamination of wheat grains with TeA, AOH, and AME. Similar findings have been reported in other regions, including China, Argentina, Canada, and Australia, confirming the global distribution of *Alternaria* toxins in cereal production systems. Although contamination levels vary significantly among studies, TeA is consistently identified as the dominant toxin in most wheat samples [21–25,27,28].

**Table 2.** Reported occurrence of major *Alternaria* mycotoxins in wheat from different countries.

Country	Sample Type	Number of Samples	Major Detected Toxins	Incidence (%)	Concentration / Reported Levels (µg/kg)	Reference
Serbia	Wheat grain	92	TeA, AOH, AME	TeA 68.5%; AOH 12.0%; AME 6.5%	Mean/max: TeA 92.4/2676; AOH 18.6/48.9; AME 39.0/70.2	[21]
Germany	Winter wheat grain	1064	TeA, AOH, AME, ALT	TeA 30.3%; AOH 8.1%; AME 3.1%; ALT 2.6%	Max: TeA 4224; AOH 832; AME 905; ALT 197	[22]
China	Wheat flour	181	TeA, TEN, AME, AOH	TeA 99.4%; TEN 97.2%; AME 91.2%; AOH 6.1%	TeA 1.76–520; TEN 2.72–129; AME 0.320–61.8; AOH 16.0–98.7	[23]
China	Wheat kernels	370	TeA, TEN, AOH, AME	Reported for all four toxins	Freshly harvested wheat from Anhui province; LC-MS/MS analysis	[24]
Albania	Wheat grain	100	AOH, AME, TEN	Albania: <LOQ	Serbia: AOH 3.3–5.3; AME 2.2–2.3; TEN 2.5–9.9	[25]

Environmental conditions play a crucial role in the development of *Alternaria* species and subsequent mycotoxin production. Warm temperatures, high relative humidity, and prolonged rainfall during flowering and grain maturation favor fungal growth and toxin biosynthesis. In addition, delayed harvesting, mechanical grain damage, insect activity, and inadequate storage conditions may further increase contamination levels. The ability of *Alternaria* species to grow under a wide range of environmental conditions contributes to their persistence throughout the wheat production chain [10,11,21,22].

Climate change has emerged as an additional factor influencing the occurrence of fungal pathogens and associated mycotoxins. Rising temperatures and altered precipitation patterns may create more favorable conditions for *Alternaria* development in regions previously considered less susceptible to contamination. Consequently, future climatic scenarios may lead to changes in fungal population dynamics and toxin occurrence, emphasizing the importance of continuous monitoring programs [10,11,29].

In wheat-derived products, *Alternaria* toxins have been detected in flour, bread, pasta, and other cereal-based foods. Although processing may reduce toxin concentrations to some extent, complete elimination is rarely achieved due to the chemical stability of several *Alternaria* metabolites. As a result, consumers may be chronically exposed to low levels of these contaminants through daily dietary intake [23,30,31].

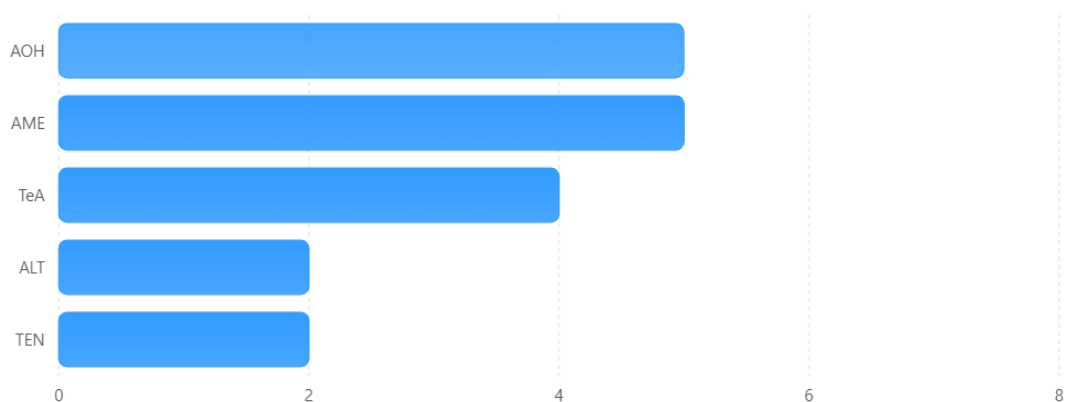
The growing body of evidence regarding the widespread occurrence of *Alternaria* mycotoxins in wheat highlights the need for systematic surveillance and comprehensive risk assessment. The frequent detection of multiple toxins, combined with the influence of environmental and climatic factors, underscores the importance of developing effective strategies for contamination prevention and control. Continued monitoring of wheat and wheat-based products is therefore essential for ensuring food safety and protecting public health [4,23,32].

#### 4. Toxicological effects and food safety implications

The increasing occurrence of *Alternaria* mycotoxins in wheat and wheat-derived products has raised significant concerns regarding their potential impact on food safety and public health. Although these toxins have received less attention than aflatoxins, ochratoxins, and Fusarium mycotoxins, numerous studies have demonstrated that several *Alternaria* metabolites possess biologically active properties that may adversely affect humans and animals [4,7,32].

Among the major *Alternaria* toxins, alternariol (AOH) and alternariol monomethyl ether (AME) have attracted considerable scientific interest due to their genotoxic and mutagenic potential. Experimental investigations have shown that these compounds can induce DNA strand breaks, oxidative stress, and chromosomal damage in mammalian cells. Such effects may contribute to the development of long-term health disorders, particularly under conditions of chronic dietary exposure. Furthermore, both AOH and AME have been reported to interfere with cellular signaling pathways and normal cell cycle regulation [17,18,33,34].

Tenuazonic acid (TeA), frequently recognized as the most prevalent *Alternaria* toxin in wheat, exhibits a different mechanism of toxicity. This toxin primarily acts by inhibiting protein synthesis, thereby affecting normal cellular functions. Several studies have demonstrated its cytotoxic effects in vitro, while animal studies have indicated potential adverse impacts on growth and physiological performance. Due to its widespread occurrence and often higher concentrations compared to other *Alternaria* toxins, TeA is considered one of the most relevant compounds from a food safety perspective (Figure 1) [19,20,32].



**Figure 1.** Relative toxicological significance of major *Alternaria* mycotoxins commonly detected in wheat.

The toxicological significance of tentoxin (TEN) and altenuene (ALT) remains less extensively studied. However, available evidence suggests that these metabolites may contribute to the overall

toxic burden associated with contaminated food and feed. The simultaneous occurrence of multiple *Alternaria* toxins in wheat further complicates risk assessment, as combined exposure may result in additive or synergistic effects. Despite increasing recognition of this issue, knowledge regarding mixture toxicity remains limited and requires further investigation [7,16,32].

The potential health risks associated with *Alternaria* mycotoxins have prompted scientific organizations to evaluate human dietary exposure. The scientific opinion published by the European Food Safety Authority highlighted concerns regarding the genotoxic properties of AOH and AME and emphasized the need for additional occurrence and toxicological data to support reliable risk assessment. Nevertheless, unlike several regulated mycotoxins, maximum permissible limits for most *Alternaria* toxins have not yet been widely established in food commodities, including wheat and wheat-based products [4,35].

From a food safety perspective, the absence of harmonized regulatory limits presents a significant challenge. The increasing detection of *Alternaria* toxins in cereals, together with projected climate-related changes favoring fungal growth, underscores the importance of implementing effective monitoring programs throughout the food production chain. Improved surveillance, standardized analytical methodologies, and expanded toxicological research are essential for reducing uncertainty and supporting future regulatory decision-making [35,36].

Overall, current evidence indicates that *Alternaria* mycotoxins represent an emerging food safety concern. Although considerable progress has been made in understanding their occurrence and biological effects, additional research is necessary to clarify exposure risks and to establish science-based regulatory measures aimed at protecting consumer health [4,7,36].

## 5. Current challenges and future perspectives

Despite significant progress in the detection and characterization of *Alternaria* mycotoxins, several challenges remain regarding their assessment and management in wheat production systems. One of the major limitations is the insufficient availability of occurrence data from different geographical regions and production environments. Although numerous studies have reported the presence of *Alternaria* toxins in wheat, substantial variability exists among reported contamination levels, making direct comparisons difficult [7,22,32].

Another important challenge relates to the limited toxicological information available for several *Alternaria* metabolites. While alternariol (AOH), alternariol monomethyl ether (AME), and tenuazonic acid (TeA) have been relatively well investigated, considerably less information is available for compounds such as tentoxin (TEN), altenuene (ALT), and numerous modified or emerging *Alternaria* toxins. Furthermore, most toxicological studies have focused on individual compounds, whereas naturally contaminated wheat samples frequently contain multiple toxins simultaneously. Consequently, the potential additive, synergistic, or antagonistic effects resulting from combined exposure remain poorly understood [32–34].

The absence of harmonized regulatory limits for *Alternaria* mycotoxins represents an additional challenge for food safety authorities and stakeholders within the cereal production chain. Although scientific organizations have highlighted potential health concerns associated with these contaminants, the current database remains insufficient to support comprehensive risk assessment and regulatory decision-making. Expanding occurrence databases and generating robust toxicological evidence should therefore remain a priority for future research [4,35,36].

Advances in analytical methodologies have significantly improved the ability to detect and quantify *Alternaria* toxins in complex food matrices. Modern chromatographic techniques, particularly liquid chromatography coupled with tandem mass spectrometry (LC-MS/MS), enable the simultaneous determination of multiple mycotoxins with high sensitivity and accuracy. The continued development of multi-mycotoxin analytical approaches will facilitate more effective monitoring and exposure assessment programs [19,37].

Climate change is expected to play an increasingly important role in the occurrence of fungal pathogens and associated mycotoxins. Changes in temperature, humidity, and precipitation patterns

may alter the geographical distribution of *Alternaria* species and influence toxin production in wheat-growing regions worldwide [10,11,29]. Therefore, future studies should focus on understanding the relationship between climatic factors and contamination risk, allowing the development of predictive models and preventive management strategies.

Future research should also emphasize integrated approaches combining agronomic practices, fungal ecology, advanced analytical techniques, and toxicological investigations. Such multidisciplinary efforts will contribute to a better understanding of *Alternaria* contamination and support the development of science-based strategies aimed at reducing exposure and ensuring the safety of wheat and wheat-derived products [32,35–37].

## 6. Conclusions

*Alternaria* mycotoxins have emerged as an important group of contaminants in wheat and wheat-derived products, attracting increasing scientific attention due to their widespread occurrence and potential implications for food safety. Although historically less studied than aflatoxins, ochratoxins, and Fusarium mycotoxins, evidence accumulated over recent decades indicates that toxins produced by *Alternaria* species are common contaminants of cereal crops and may represent a significant concern for both human and animal health. The growing number of studies reporting the presence of these compounds in wheat from different geographical regions highlights the global nature of this issue and emphasizes the need for continued surveillance and research.

Among the various metabolites produced by *Alternaria* species, alternariol (AOH), alternariol monomethyl ether (AME), and tenuazonic acid (TeA) are considered the most relevant due to their frequent occurrence and documented biological activity. Numerous investigations have demonstrated that these toxins may exhibit cytotoxic, genotoxic, mutagenic, and other adverse effects, suggesting that chronic dietary exposure could pose potential health risks. In particular, the genotoxic properties of AOH and AME have attracted considerable attention from the scientific community and regulatory bodies, while TeA has been identified as one of the most prevalent *Alternaria* toxins in wheat and cereal-based foods.

The occurrence of *Alternaria* mycotoxins in wheat is influenced by a complex interaction of environmental, agronomic, and post-harvest factors. Temperature, humidity, rainfall patterns, fungal species composition, and storage conditions all contribute to contamination levels observed in different regions and production systems. Furthermore, ongoing climate change may significantly alter the distribution and prevalence of *Alternaria* species, potentially increasing contamination risks in some wheat-growing areas. These developments further underline the importance of implementing effective monitoring programs and preventive management strategies throughout the wheat production chain.

Despite significant advances in analytical methodologies, several challenges remain. The availability of occurrence data is still limited for many regions, and substantial variability among studies complicates comparisons and exposure assessments. In addition, most toxicological investigations have focused on individual toxins, whereas natural contamination scenarios often involve the simultaneous presence of multiple *Alternaria* metabolites. Consequently, the potential combined effects of co-occurring toxins remain insufficiently understood and require further investigation.

Another important issue is the current lack of harmonized regulatory limits for most *Alternaria* mycotoxins. While scientific evidence regarding their occurrence and toxicity continues to expand, additional toxicological and exposure data are necessary to support comprehensive risk assessments and the establishment of science-based regulations. Such efforts will be essential for improving consumer protection and strengthening food safety policies.

In conclusion, *Alternaria* mycotoxins should be considered emerging contaminants of increasing relevance in wheat production and food safety. Continued research focused on occurrence patterns, toxicological characterization, analytical monitoring, and climate-related impacts will be crucial for

reducing existing knowledge gaps and supporting effective risk management. A multidisciplinary approach involving researchers, food producers, regulatory agencies, and public health authorities will be necessary to ensure the safety and quality of wheat and wheat-derived products in the future.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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