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Review

Reducing fumonisin contamination in Brazilian maize: The impact of Codex standards and regulatory frameworks

Liliana de Oliveira Rocha [a,*], Marta Hiromi Taniwaki [b], Michael Ennis [c], Ligia Lindner Schreiner [d], Farid El Haffar [c]

[a] *Laboratory of Microorganisms and Mycotoxins, Department of Food Science and Nutrition, School of Food Engineering, University of Campinas, Campinas, SP, Brazil*
[b] *Institute of Food Technology (ITAL), Campinas, SP, Brazil*
[c] *Secretariat of the Codex Alimentarius Commission, Food and Agriculture Organization of the United Nations, Rome, Italy*
[d] *Brazilian Surveillance Agency (ANVISA), Brasília, DF, Brazil*

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ABSTRACT

Fumonisins are mycotoxins produced primarily by the *Fusarium fujikuroi* species complex in maize, and contamination poses significant health risks and economic implications. This review explores Brazil's comprehensive approach to reducing fumonisin contamination in maize, particularly the strategies adopted by the Brazilian Surveillance Agency (ANVISA), thanks to its participation in and the work of the Codex Committee on Contaminants in Foods (CCCF). Through collaborative efforts with several stakeholders, Brazil has successfully reduced fumonisin levels over the past thirty years, improving food safety for its population and exports. The recorded data indicate that the mean levels of fumonisins were 2692.1 μg/kg during the years 1991–2010, while the mean levels decreased to 685.4 μg/kg from 2011 to 2022. Based on this, significant progress has been achieved; nevertheless, challenges persist, particularly concerning enforcement and compliance disparities across the country. In this respect, active engagement from academia, industry, and regulatory bodies is crucial for raising awareness about health and economic risks linked to mycotoxin contamination. Strengthening monitoring efforts and sustainable collaborations are also recommended to further increase fumonisin control and food safety.

1. Introduction

Brazil is considered the strongest economy in Latin America, largely due to the agricultural sector. The country is a leading producer of maize, coffee, sugarcane, soybean, beef, and poultry (FAOSTAT, 2022a; OECD, 2024). Small-scale farmers contribute to 77 % of agricultural establishments and employ three-quarters of the farm labor force in the country (IBGE, 2017). Nevertheless, the primary engine of growth in the sector comes from corporate agriculture, driven by export commodities (Arias et al., 2017). In this respect, the top three commodities produced and exported by Brazil are sugar cane, soya, and maize (FAOSTAT, 2022b).

Maize is an essential staple crop, supporting millions as a primary food source, with an annual average production of 1,228.1 million metric tons (MMT) and consumption of 1,204.3 MMT as of 2023–2024 (USDA, 2024). Brazil has more than doubled its production in the last 20 years, reaching a volume of 109,420,717 tonnes in 2022, thereby becoming the 3rd largest producer and the 2nd largest exporter globally, with exports exceeding USD 12 billion (FAOSTAT, 2022c). This growth was achieved due to improvements in grain quality and compliance with international standards. A multidisciplinary approach that involved the participation of the Brazilian Codex delegation, led by the Brazilian Surveillance Agency (ANVISA) to the Codex Committee on Contaminants in Food (CCCF) was a crucial factor in enhancing producers' awareness of the related Codex texts, which contributed to the improvement of grain quality. This successful collaborative model is a potential framework for similar initiatives in other countries.

Nonetheless, the production of maize may be constrained by various factors, including drought, low soil fertility, insect pests, and diseases (García-Lara et al., 2019). Most maize-related diseases are linked to fungi, such as *Aspergillus* and *Fusarium,* causing ear and/or kernel rots (Munkvold, 2003). Species belonging to these genera are notorious for producing mycotoxins, toxic secondary metabolites, that may accumulate during cereal infection in the field and grain storage under certain

* Corresponding author.
E-mail address: lrocha@unicamp.br (L. de Oliveira Rocha).

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conditions, affecting the value and marketability of the product, therefore causing significant economic losses (Palumbo et al., 2020).

The *Fusarium fujikuroi* species complex (FFSC) is widely reported in maize, with some members consistently producing fumonisins such as *F. verticillioides* and *F. proliferatum* (Desjardins, 2006). Particularly, *F. verticillioides* is the most common species associated with maize worldwide and can produce high levels of fumonisins (Leslie & Summerell, 2006), with multiple factors such as environmental conditions, water availability, and type of cultivar playing crucial roles in fumonisin contamination (Dinolfo et al., 2022). Moreover, even within intact maize kernels, there is a potential for low fumonisin occurrence due to *F. verticillioides* in healthy and diseased plants (Yli-Mattila & Sundheim, 2022).

Among over 28 fumonisin analogs identified, fumonisin B1 (FB1) is the predominant and most toxic compound, followed by fumonisins B2 (FB2) and B3 (FB3) (Voss et al., 2017). These mycotoxins have been reported to cause several toxic effects, with the International Agency for Research on Cancer (IARC) classifying fumonisin B1 (FB1) as a group 2B carcinogen (IARC, 2002).

At certain levels, fumonisins render feed and food products unacceptable due to their potential toxic effects. Therefore, mitigating the risks associated with fumonisin contamination is crucial and requires a comprehensive approach that spans from agricultural practices through harvest and storage to processing and usage. While strategies to manage mycotoxins after harvesting are possible, the most efficient approach initiates in the field and requires measures throughout the maize production chain (Cleveland et al., 2003).

The Codex Alimentarius Commission (CAC) establishes international standards, guidelines, and codes of practice (COP) to address, among others, issues related to mycotoxin contamination, management, and the potential effects on public health and global trade (Clarke & Fattori, 2013). Several Codex texts refer to the prevention and/or reduction of mycotoxins in a range of commodities, and member countries should take measures at the national level to align their regulations with the Codex standards and to adopt and adapt the COP to the local context (López-Garcia, 2022). Moreover, since 2021, the CAC has implemented a framework to provide data on the use of Codex texts to help Members and Observers better understand the impact of these texts (FAO/WHO, 2023).

The Codex standards significantly influenced ANVISA's strategies concerning the Maximum Levels (MLs) for mycotoxins in food and beverages (ANVISA, 2020a). This led to a revision of Brazilian regulations in 2011, establishing limits for six mycotoxins across various food categories, including fumonisins in maize and its by-products (Taniwaki et al., 2019).

Additionally, ANVISA implemented a strategic plan that began with relatively high MLs, gradually decreasing the acceptable levels each year. This innovative approach, combined with adopting Good Agricultural Practices (GAP) and Good Manufacturing Practices (GMP), has led to a remarkable reduction in fumonisin contamination to levels aligned with international standards.

The primary objective of this review is to explore the impact of the regulatory frameworks and initiatives implemented by ANVISA, using the related Codex Alimentarius standards and COP, on the management of fumonisin contamination in Brazil over the past three decades. Specifically, this manuscript will delve into the effectiveness of these guidelines and regulations in reducing fumonisin levels, supporting food safety, and the global trade of maize products from Brazil.

2. The Codex Alimentarius

The Codex Alimentarius is an internationally recognized compendium of standards, guidelines, and COP that pertain to food safety and quality. The Codex Alimentarius Commission was established in 1963 as part of the FAO and WHO joint program on food safety. The statutory purpose of the Codex Alimentarius is to protect consumer health and ensure fair practices in the food trade (FAO/WHO, 2018).

The food safety standards set by the CAC encompass permissible levels of food additives, pesticide residues, and contaminants in food based on rigorous scientific risk assessments conducted by independent experts. Additionally, the Codex provides nutritional guidelines, which include requirements for nutritional labeling and regulations on health claims, thereby ensuring that consumers have access to accurate and non-misleading information. The Codex Alimentarius also includes several COP on different subjects, including detailed practices to ensure food safety throughout the supply chain (FAO, 2024a).

The CAC, the governing body of the Codex, is composed of member countries and observer organizations. The Commission meets annually to adopt new standards and review existing ones (Godefroy, 2014). Codex is, therefore, essential to promoting equitable access to markets for both low- and middle-income countries (LMICs) and high-income countries (HICs); furthermore, collaborative efforts among governments, international organizations, research institutes, and private stakeholders are crucial in establishing frameworks that support economic growth (Godefroy, 2014). In this context, the CAC plays a crucial role in the global harmonization of food standards. In addition, the standards set by Codex are instrumental in resolving international trade disputes related to food safety and quality, as they are used as references in World Trade Organization (WTO) agreements[1] (FAO, 2024b).

The credibility of Codex texts is primarily derived from rigorous scientific data collected globally, ensuring that decisions are relevant at international and regional levels (Godefroy, 2014). FAO and WHO are responsible for risk assessment through advisory bodies such as the Joint Expert Committee on Food Additives (JECFA), composed of independent experts, that provide the scientific foundation for addressing food safety issues (Lee et al., 2021). The scientific assessment process emphasizes transparency and inclusiveness. Each step is documented, and the findings are disseminated to food regulators and stakeholders worldwide through various formats, including printed materials and online platforms (FAO/WHO, 2018).

The primary focus of the CCCF is to establish MLs and guidelines for contaminants and naturally occurring toxicants, including mycotoxins, in food and feed; develop priority lists of contaminants for risk assessment; evaluate methods for the analysis and sampling of contaminants; create standards or COP for related subjects; and address additional issues assigned by the Commission concerning contaminants and toxicants in food and feed (FAO/WHO, 2019).

Currently, 188 nations have joined the Codex as Member Countries, and the European Union has joined as a Member Organization, contributing to the development and continuous evolution of the Codex texts (FAO/WHO, 2018). Although the Codex documents are recommendations for voluntary adoption by members, they often provide a foundation for national legislation (FAO/WHO, 2018). Brazil has been a member since 1968, contributing to several of the Codex texts, particularly for commodities of significant interest to the country, including maize (ANVISA, 2020a).

The Coordination and Executive Secretariat of the Brazilian Codex Committee (CCAB) is led by the Brazilian National Institute of Metrology, Normalization and Industrial Quality (INMETRO), while the Ministry of Foreign Affairs (MOFA) represents the Contact Point for the Brazilian Committee at the CAC Other key CCAB members include the Ministry of Agriculture and Livestock (MAPA), ANVISA, several agricultural and industrial bodies (e.g., the National Confederation of Industry and Brazilian Association of Food Industries-ABIA); and

[1] The two WTO agreements of most significance for international food trade and Codex are (i) the Agreement on the Application of Sanitary and Phyto-Sanitary Measures (SPS), which concerns measures applied to protect human, animal and plant health; and (ii) the Agreement on Technical Barriers to Trade (TBT), which refers to technical regulations and conformity assessment procedures and applies to all commodities, not just food.

Consumer Protection Entities indicated by the National Council for Metrology, Standardization and Industrial Quality (CONMETRO) (INMETRO, 2024). The CCAB mimics the CAC structure, with subcommittees established at the national level against each Codex subsidiary body. A subcommittee for contaminants in foods is led by ANVISA with the participation of different stakeholders, including MAPA, INMETRO, public laboratories, ABIA, consumer groups, private sector representatives, academia, research and extension institutes, and others, depending on discussions held at CCCF and needs for specific expertise (ANVISA, 2020b).

3. The code of practice for the prevention and reduction of mycotoxin contamination in cereals (CXC 51–2003)

The CAC adopted the Code of Practice for the Prevention and Reduction of Mycotoxin Contamination in Cereals (CXC 51–2003) in 2003. This code describes strategies to reduce mycotoxin contamination in cereals, emphasizing good practices from pre-harvest through post-harvest stages (FAO/WHO, 2003). To effectively implement this code, it is important for national authorities, producers, distributors, and processors to adhere to GAP and GMP, taking into account their specific agricultural conditions. Moreover, grain producers must recognize that proper GAP, along with effective storage and handling procedures, are the first line of defense against mycotoxin contamination. Education on the environmental factors that promote the growth of toxigenic fungi is also necessary. Additionally, the use of validated analytical methods and appropriate sampling plans is essential for producers and processors to quickly assess mycotoxin levels and avoid disruptions in grain shipment operations (FAO/WHO, 2003).

In 2008, the CCCF established an electronic working group (EWG) led by Brazil and opened it to all members to prepare a discussion paper that would include an overview of the available data concerning fumonisin contamination. These discussions facilitated Brazil's efforts to revise its mycotoxin regulations, which were limited to MLs of aflatoxins in peanuts, maize, and milk at that time (FAO/WHO, 2008; Brazil, 2002).

In 2009, the Brazilian delegation outlined the main aspects considered in the discussion paper, including occurrence data, analytical methods, sampling plans, intake levels, exposure and risk assessment, risk management considerations, as well as agricultural, technological, and commercial aspects of fumonisin contamination (FAO/WHO, 2009). Although the discussions were suspended in 2010, it was noted that it would be helpful to assess the effectiveness of the CXC 51–2003 to avoid the formation of fumonisins in maize and its by-products and to gather more recent occurrence data on fumonisins (FAO/WHO, 2009; FAO/WHO, 2010). In 2014, the EWG led by Brazil, with the United States of America and Nigeria as co-chairs, emphasized the need for CXC 51–2003 updates, including additional measures for the prevention and reduction of mycotoxins, such as the incorporation of Hazard Analysis and Critical Control Point (HACCP) system, the use of biological control, and predictive models; in 2016, the revisions were adopted (FAO/WHO, 2014; FAO/WHO, 2016). Further amendments were included in 2017 to address GAP practices for controlling ergot alkaloids (FAO/WHO, 2017).

Brazil's active participation in the discussions within the CCCF was essential for influencing the establishment of MLs for fumonisins in maize at a national level. By leading initiatives, such as the EWG established in 2008 to gather and analyze data on fumonisin contamination, Brazil has played a crucial role in addressing food safety challenges posed by mycotoxins. This involvement not only supported the revision of national regulations but also promoted collaboration among regulatory bodies, industry stakeholders, and research partners. The following sections will address Brazilian maize production, examining the challenges associated with cultivation and the issues surrounding fumonisin contamination. Furthermore, the strategies employed by the Brazilian government, based on the guidelines outlined by the Codex Alimentarius, to effectively address the fumonisin problem over the years will be discussed.

4. Overview of the Brazilian maize production and challenges

Maize is one of the most extensively cultivated crops worldwide, with the United States, China, and Brazil contributing to 64 % of the world's total maize output (USDA, 2024). A large portion of maize in Brazil is exported; in addition, this crop is consumed domestically, primarily for animal feed, food and, more recently, for bioethanol production (Allen & Valdes, 2016). Highlighting that during the last 20 years, the production, domestic consumption, and exports have more than doubled, establishing Brazil as the third-largest producer and the second-largest exporter of maize worldwide (FAOSTAT, 2022c; CONAB, 2024a; CONAB, 2024b).

Although maize is cultivated across the country, the largest producing states are Mato Grosso, Paraná, Goiás, Mato Grosso do Sul, and Minas Gerais (located in the Midwest, South, and Southeast regions of Brazil), contributing to 78 % of the national production (Fig. 1) (CONAB, 2024a). These states are also responsible for most of the country's exports. In contrast, in the North and Northeast regions, small-scale farmers play a significant role in cultivating maize for subsistence purposes, indicating a growing significance of maize in both domestic and global contexts (CONAB, 2024a).

Given Brazil's vast land area and climatic conditions, maize is cultivated year-round, allowing three annual crop seasons. The second season was introduced in the 1980 s, and nowadays, it accounts for 77 % of Brazil's production, while the first and third contribute 21 % and 2 %, respectively (CONAB, 2024a; Mattos & Silveira, 2018).

In the Southeast and Midwest regions of Brazil, planting for the first growing season occurs between October and November, coinciding with the rainy period of the year. In the Southern region, planting typically occurs at the end of August, with harvesting from February to April (Landau & Moura, 2020). For the second season, known as "safrinha", planting occurs between February and March, with harvesting from May to August. In areas with two annual seasons, maize is usually cultivated after a primary crop, usually soybeans (Landau & Moura, 2020).

The third growing season occurs in the Northern and Northeastern regions of Brazil, particularly in the states of Alagoas, Bahia, Pernambuco, Sergipe, and Roraima, with sowing happening between April and June and harvest between August and November (CONAB, 2021). Although the 3rd season is not yet as significant as that of the first and second ones, maize production in these regions has quadrupled since the 2000 s, and the cultivated area tends to expand in the coming years (CONAB, 2024b; Conab, 2024c).

Maize yields depend on the interactions of abiotic factors (such as climate and soil) and biotic factors (including pests and diseases), along with various management practices (Andrea et al., 2018). The climate significantly influences crop productivity as a crucial abiotic factor. The El Niño–Southern Oscillation (ENSO) phenomenon, known for its climatic pattern alterations in tropical and mid-latitude zones, plays a pivotal role in shaping Brazilian agricultural outcomes (Berlato et al., 2005). The contrasting phases of ENSO, El Niño and La Niña, are associated with elevated and reduced precipitation levels, respectively. Depending on specific conditions, these precipitation anomalies can impact plant health dynamics, potentially exacerbating plant disease severity (CONAB, 2024a).

Additional constraints, such as pest infestation, low soil fertility, and diseases may significantly affect yield annually (Daniel et al., 2018). To address these issues, management strategies include the use of resistant cultivars, adjusting sowing dates, implementing thorough soil preparation, optimizing plant density, incorporating biostimulants, employing irrigation and fertilizers, and conducting rigorous integrated pest management for optimal crop health (CONAB, 2024a).

Despite current crop protection practices, maize yield losses may occur due to various diseases, including foliar diseases, smuts, stalk,

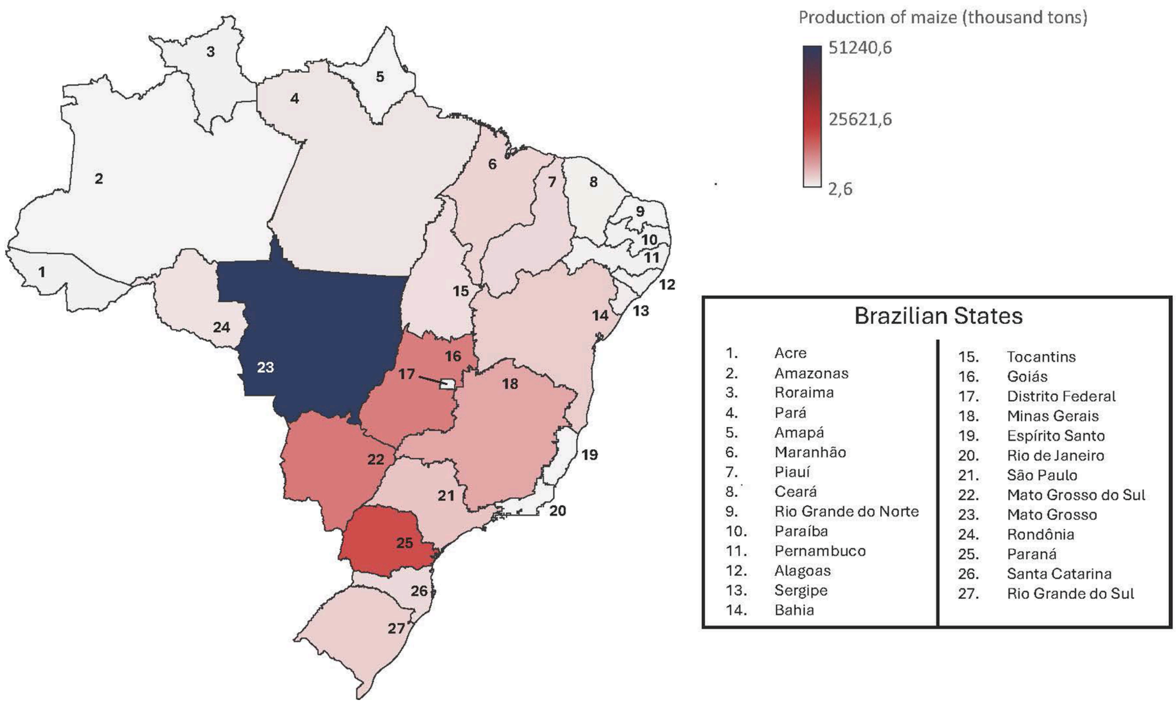

Fig. 1. Map of Brazil indicating the states and major maize producers: Mato Grosso (23), Paraná (25), Goiás (16), Mato Grosso do Sul (22), and Minas Gerais (18). The production of maize by each state is designated as a thousand tons.

kernel, and ear rots (Juroszek and Tiedemann, 2013). Kernel rots and ear rots can be caused by toxigenic fungi, such as *A. flavus* and various *Fusarium* species, which are notorious for producing aflatoxins and fumonisins, respectively, and these rots are usually associated with increased mycotoxin contamination (Amaike & Keller, 2011; Munkvold, 2003). For instance, *F. verticillioides* is reported as the most common causal agent of ear rots in maize-growing areas of the world (Lanubile et al., 2014), contributing to substantial economic losses and posing a threat to food and feed safety due to its consistent production of fumonisins (Munkvold, 2003).

Furthermore, amidst the challenges posed by these factors, it is important to highlight the significance of small-scale production as a vital economic endeavor across various Brazilian regions, which plays an important role in supporting employment opportunities and income generation (Paraguassu-Chaves et al., 2020). Constraints on small-scale farming encompass inadequate technological processing infrastructure, limited farmer education levels, and restricted access to technical resources. Therefore, disparities exist between undercapitalized and well-funded agricultural entities, highlighting the need for strategic programs to elevate farmers' understanding of GAP and modern technologies, alongside enhanced technical support, to strengthen their development and competitiveness (Futemma et al., 2020; Pereira et al., 2012).

In this respect, the use of Codex texts as a fundamental framework to guide food legislation, policies, programs, and practices worldwide is important in promoting fair practices in the food trade and consumer health protection (FAO, 2024b). One such example is the implementation of these texts to mitigate mycotoxin contamination through GAP and GMP, effectively reducing losses from fungal diseases and mycotoxin contamination (FAO/WHO, 2003). While most stakeholders across all regions of Brazil demonstrate good knowledge of the principles specified in the COP, it is noteworthy that small-scale producers still lack adequate familiarity. Therefore, additional efforts to disseminate information among this group would be beneficial.

4.1. Epidemiology of the Fusarium fujikuroi species complex in maize and fumonisin production

Various toxigenic fungi may cause ear and kernel rots in maize, leading to significant economic losses. This issue is further exacerbated due to the potential for mycotoxin contamination, impacting the grain's quality and marketability.

Aspergillus ear or kernel rot, caused by species in *Aspergillus* Section *Flavi*, primarily *A. flavus*, occurs in warm and dry weather and is commonly linked to aflatoxin contamination (Amaike & Keller, 2011). *Gibberella* ear rot, or red ear rot, caused by the *Fusarium sambucinum* species complex, predominantly *F. graminearum*, occurs in cooler and humid areas, with the silk channel acting as a primary route for *F. graminearum* infection. This disease is often associated with zearalenone and type B trichothecene contamination (Munkvold, 2014).

Members of the FFSC cause *Fusarium* ear rot or pink ear rot. The most predominant species is *F. verticillioides*; nevertheless, *F. proliferatum* and *F. subglutinans* can also be found. *F. verticillioides* and *F. proliferatum* are mainly isolated from drier and warmer conditions. These two species are also isolated from temperate regions, whereas *F. subglutinans* and *F. temperatum* are more frequent in humid and cooler conditions (Czembor et al., 2015). Other FFSC members associated with ear rot are *F. andiyazi, F. nygamai,* and *F. thapsinum* (Leyva-Madrigal et al., 2015; Venturini et al., 2017), all capable of producing fumonisins at variable levels (Leslie & Summerell, 2006; Stępień et al., 2011).

Fusarium verticillioides is one of the most common species of fungi isolated from maize worldwide and is particularly prevalent in Brazilian maize (Cao et al., 2014; Van Der Westhuizen et al., 2003; Lanza et al., 2014). The high incidence of this fungus in maize is due to multiple infection pathways, which are systemic from seeds, through plant wounds, or silk channels. In addition, *F. verticillioides* can degrade maize-produced antimicrobial compounds, contributing to its success as a pathogen (Leslie & Summerell, 2006).

Besides causing ear rot symptoms, *F. verticillioides* can also be recovered from asymptomatic plants as an endophyte. Depending on the environment, fungus, and host relationship, this endophytic state may be transient. In severe drought or unfavorable plant growth conditions, the balance between the two organisms may be disrupted, leading to varying degrees of pathological responses in maize (Bacon et al., 2008). Under these circumstances, higher levels of fumonisins are observed, particularly when drought occurs during the grain-filling stage and is associated with insect infestation (Munkvold, 2003). Moreover, the majority of *F. verticillioides* strains produce significant amounts of fumonisins, even in asymptomatic plants, thus increasing the complexity of fumonisin contamination in maize during preharvest (Lanubile et al., 2017).

Studies have shown that *F. verticillioides* is more efficient in producing FB1 between 20 °C and 30 °C, with water activity (aw) > 0.95 (Faneli et al., 2012; Marin et al., 2004); if aw exceeds 0.97, *F. verticillioides* can synthesize fumonisins at 15 °C (Samapundo et al., 2005). Similarly, *F. proliferatum* has the capacity to synthesize fumonisins in the 15–30 °C range at 0.97 aw (Marin et al., 1999); however, significantly higher fumonisin yields were observed at 22 °C compared to 30 °C (Samapundo et al., 2005).

In general, fumonisin production is highly correlated with aw (Samapundo et al., 2005); in this regard, during maize cultivation at the ripening stage of maize kernels, the moisture content is around 45 %, allowing *F. verticilloides* and *F. proliferatum* to produce fumonisins until harvest (Dinolfo et al., 2022; Marin et al., 2004). Insects and other environmental factors that stress the plant may enhance fumonisin contamination (Marin et al., 2004; Munkvold, 2003). Afterward, the time between harvest and drying must be as short as possible. Once dried and stored, temperature must be controlled to avoid water condensation and further fungal growth. FB1 production in dry maize is unlikely, with *F. verticillioides* counts reducing over storage time (Carbas et al., 2021). Nevertheless, postharvest fumonisin production has been reported to occur when storage conditions are inappropriate (Mylona et al., 2012; Tran et al., 2021).

The impact of the FFSC causing ear rots in maize poses a challenge due to the potential fumonisin contamination. This issue is significant in LMICs and HICs. In middle-income economies, such as Brazil, where agricultural practices may vary across regions and even between producers, the risk of fumonisin contamination requires comprehensive and continuous monitoring and management. Therefore, understanding the interactions between fungi, environmental factors, and host plants is essential to mitigate mycotoxin contamination risks in maize production (Li et al., 2024).

4.2. Fumonisins: Importance and occurrence in Brazilian maize

Maize and its by-products may contain substantial amounts of fumonisins, particularly because *F. verticillioides* and other FFSC fumonisin-producing species are closely associated with maize (Leslie & Summerell, 2006). Most fumonisin-producing species are members of the FFSC, but strains of *F. oxysporum* and *Aspergillus niger* have been reported to produce these mycotoxins in different commodities, such as asparagus and grapes, respectively (Mogensen et al., 2010; Proctor et al., 2008).

Fumonisin B1 (FB1) is typically the most abundant, comprising over 60 % of fumonisins in maize and its by-products and the most important from a toxicological point of view; despite FB2 and FB3 being found in lower frequency and levels, FB2 is still more common than FB3 (Voss et al., 2017). Fumonisins are polyketide-derived molecules; their chemical structure is primarily composed of a long carbon backbone with hydroxyl groups and esterified propane-1,2,3-tricarboxylic acid (tricarballylic acid, TCA) groups. The B series molecules exhibit solubility in polar solvents (Maragos et al., 2022); in addition, these compounds present certain thermal stability, with degradation by usual thermal processing technologies varying according to the temperature and treatment applied (Maragos et al., 2022; Yang et al., 2022).

The toxicity of fumonisins is mainly attributed to the inhibition of ceramide synthase, an enzyme crucial for sphingolipid biosynthesis. This results in the accumulation of sphingosine and sphinganine while reducing ceramide levels, causing various harmful consequences, including neurotoxicity, carcinogenicity, and immunosuppression (Mullen et al., 2012; Voss et al., 2017). Inequine, fumonisins cause equine leukoencephalomalacia, a fatal condition characterized by necrosis in the brain's white matter (Marasas et al., 2004). In swine, they cause porcine pulmonary edema, hydrothorax, liver damage, and reduced feed intake. Fumonisins are also hepatotoxic and nephrotoxic to mice, rats, rabbits, and pigs (Li et al., 2024). Despite the unclear impact of fumonisins on human health (Voss et al., 2017), they can be a potential cause of esophageal cancer and were associated with growth impairment and neural tube defects in populations dependent on maize as a primary dietary staple (Marasas et al., 2004; Sydenham et al., 1990; Voss et al., 2017). Considering these observations, the International Agency for Research on Cancer (IARC) classified FB1 as group 2B, possibly carcinogenic to humans (IARC, 2002).

Currently, the Joint FAO/WHO Expert Committee on Food Additives (JECFA) has established a Provisional Maximum Tolerable Daily Intake (PMTDI) of 2 μg/kg bw for FB1, FB2 and FB3, alone or in combination (WHO, 2017). Conversely, the European Food Safety Authority (EFSA) set a Tolerable Daily Intake (TDI) of 1 μg/kg bw for FB1, FB2, FB3, and FB4 (EFSA, 2018). In addition, maximum levels (MLs) of fumonisins in maize, maize flour, and maize meal have been recommended by the Codex Alimentarius through its General Standard for Contaminants in Food and Fees CXS 193–1995 (FAO/WHO, 1995), and various authorities worldwide, including Brazil, established MLs for fumonisins. Since 2011, ANVISA has set MLs for fumonisins in maize and derived products (Brazil, 2022).

In this context, occurrence data is essential for evaluating risk assessments, ensuring fair trade practices for producers, and establishing appropriate national MLs for different food products. Table 1 summarises studies on fumonisin contamination in Brazilian maize and its by-products over the past thirty-three years.

Brazil's first reports on fumonisin contamination were published in 1991, primarily in samples intended for animal consumption. At that time, most analyzed samples were associated with ELEM, with some showing fumonisin levels exceeding 50,000 μg/kg (Sydenham et al., 1992).

Concerning levels were reported between 1991 and 2010, before ANVISA implemented MLs on fumonisins in food (Table 1; Fig. 2). The minimum and maximum concentrations varied from non-detected (below the method's limit of detection/LOD reported in the cited studies) (mean: 684.6 μg/kg, median: 157 μg/kg) to 78,920 μg/kg (mean: 11,826.1 μg/kg, median: 6,450 μg/kg), noting that 38 % of the maximum levels were > 10,000 μg/kg (Table 1).

During the period of 2011 to 2022, the minimum and maximum concentrations ranged from non-detected (below the LOD reported in the cited studies) (mean: 76.5 μg/kg, median: 54.7 μg/kg) to 66,274 μg/kg (mean: 5,095.9 μg/kg, median: 1,277.7 μg/kg); this high concentration was observed in a single unprocessed maize sample during the 2012–2013 season (Oliveira et al., 2017). Two other high concentrations (54,000 and 31,420 μg/kg) were observed in maize destined to feed collected from a small-scale farm and Brazilian feed producers, respectively (Franco et al., 2019; Biscoto et al., 2022). In addition, the mean of the maximum levels was twice as low as the one recorded from 1991 to 2010, and only 8.5 % of the maximum levels were > 10,000 μg/kg (Table 1).

Mean fumonisin levels fluctuated across the recorded years (Fig. 2). These inconsistencies may be associated with climatic variations, farming practices, GAP, and GMP, which may change fungal populations as well as mycotoxin occurrence and concentrations. Nevertheless, a trend in fumonisin reduction was observed, especially after 2011, with lower mean levels observed during 2016–2022 (Fig. 2).

In addition, we partitioned the data into unprocessed and processed maize to assess the variations in fumonisin mean levels across successive five-year periods. As expected, higher levels were observed in unprocessed maize, with mean concentration ranging from 832.7 μg/kg

Table 1
Occurrence and levels of fumonisins (FB1 or FB1 + FB2, when available) in Brazilian maize and its by-products from 1991 to 2022.

		Fumonisin levels (FB1 or FB1 + FB2, when available)					
Sample type	Number of samples/ positive samples (% of positive samples)	Minimum levels (μg/kg)	Maximum levels (μg/kg)	Mean levels [a] (μg/kg)	Location (State)	Year of sampling	Reference
Corn for animal feed (associated with ELEM)	21/20 (95.2)	< 500[b]	50,500	11747,6	Paraná	1991–1995	Sydenham et al., 1992
Unprocessed corn	39/39 (100)	600	12,550	na [c]	Paraná	1991	Hirooka et al., 1996
Unprocessed corn	8/8 (100)	4900	18,520	10,590	Mato Grosso do Sul	1991	Hirooka et al., 1996
Corn for animal feed	27/27 (100)	2320	16,640	6370	Paraná	1991	Ono et al., 2004
Unprocessed corn	105/105 (100)	310	8690	2920	São Paulo	1995	Camargos et al., 2000a
Unprocessed corn	150/147 (98)	< 96	22,600	5357	Paraná	1995	Ono et al 2001
Unprocessed corn	109/109 (100)	130	20,380	5030	Paraná	1995	Ono et al., 2006
Corn for animal feed (associated with ELEM)	na	na	53,000	na	Rio Grande do Sul	1996	Mallmann et al., 1999
Unprocessed corn	36/36 (100)	700	22,600	10,100	Paraná	1996	Ono et al., 2002
Unprocessed corn	267/94 (35.2)	< 400	78,920	8860	Rio Grande do Sul	1996–1998	Mallmann et al., 2001
Unprocessed corn	87/87 (100)	1270	52,530	9150	São Paulo	1998	Camargos et al., 2000a
Unprocessed corn	23/23 (100)	2080	34,290	7470	São Paulo	1997–1998	Camargos et al., 2001
Unprocessed corn	212/210 (99.1)	< 3.6	6100	2200	Central, South and Southeast Brazil (contamination was not separated by region)	1998	Vargas et al., 2001
Unprocessed corn	195/176 (90.2)	< 20	49,310	na	São Paulo	1999	Orsi et al., 2000
Canned sweet corn	11/2 (18.1)	< 20	210	70	São Paulo	1999	Machinski & Soares, 2000
Corn flakes	4/1 (25)	< 20	660	170	São Paulo	1999	Machinski & Soares, 2000
Corn flour	13/10 (77)	< 20	1460	220	São Paulo	1999	Machinski & Soares, 2000
Corn grits	2/2 (100)	170	1230	2290	São Paulo	1999	Machinski & Soares, 2000
Corn meal	9/9 (100)	560	4930	2890	São Paulo	1999	Machinski & Soares, 2000
Degerminated corn	11/8 (73)	< 20	4520	840	São Paulo	1999	Machinski & Soares, 2000
Popcorn	9/4 (44.4)	< 20	1720	330	São Paulo	1999	Machinski & Soares, 2000
Precooked corn flour	6/4 (66.7)	< 20	1790	1260	São Paulo	1999	Machinski & Soares, 2000
Pamonha	7/0	< 20	< 20	< 20	São Paulo	1999	Machinski & Soares, 2000
Curau	2/0	< 20	< 20	< 20	São Paulo	1999	Machinski & Soares, 2000
Unprocessed corn	57/52 (91.2)	< 50	17,690	1170	São Paulo	1999	Almeida et al., 2002
Unprocessed corn	35/35 (100)	2200	13,400	4310	Minas Gerais	1999	Pinto et al., 2007
Canjica corn	9/9 (100)	20	530	190	Pernambuco	1999–2001	Kawashima and Soares, 2006
Corn flour	12/10 (83.3)	< 12	150	61	Pernambuco	1999–2001	Kawashima and Soares, 2006
Corn flakes	29/29 (100)	60	870	370	Pernambuco	1999–2001	Kawashima and Soares, 2006
Corn meal	11/10 (91)	< 12	8600	2400	Pernambuco	1999–2001	Kawashima and Soares, 2006
Cracked corn	12/12 (100)	30	1400	410	Pernambuco	1999–2001	Kawashima and Soares, 2006
Unprocessed corn	90/90 (100)	20	18,740	2890	Santa Catarina	2000	Westhuizen et al., 2003
Corn meal	30/30 (100)	1310	19,230	6170	São Paulo	2000	Bittencourt et al., 2005
Corn flour	30/30 (100)	590	8880	2740	São Paulo	2000	Bittencourt et al., 2005
Unprocessed corn	35/34 (97.1)	na	17,400	5140	Mato Grosso	2001	Cortês et al., 2002
Corn flour	47/44 (93.6)	< 40	21,823	4774	Santa Catarina	2001	Scaff et al., 2004
Canjica	12/11 (91.7)	< 40	2237	732	Santa Catarina	2001	Scaff et al., 2004
Corn flakes	11/11 (100)	157	5856	1307	Santa Catarina	2001	Scaff et al., 2004

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Table 1 (*continued*)

Sample type	Number of samples/ positive samples (% of positive samples)	Fumonisin levels (FB1 or FB1 + FB2, when available) Minimum levels (μg/kg)	Maximum levels (μg/kg)	Mean levels [a] (μg/kg)	Location (State)	Year of sampling	Reference
Popcorn	12/11 (91.7)	< 40	9773	2872	Santa Catarina	2001	Scaff et al., 2004
Corn meal for baby food	117/117 (100)	60	8039	1114	São Paulo	2002	Castro et al., 2004
Unprocessed corn	435/435 (100)	20	18,780	2230	Paraná	2003	Ono et al., 2008
Unprocessed corn	245/245 (100)	20	18,780	2930	Paraná	2003	Silva et al., 2008
Unprocessed corn	150/150 (100)	80	18,780	2830	Paraná	2003	Moreno et al., 2009
Corn for animal feed	480/469 (97.8)	< 2	5500	na	Rio de Janeiro	2003–2004	Oliveira et al., 2006
Corn meal	73/73 (100)	267	6170	1860	Federal District	2003–2005	Caldas et al., 2007
Snacks	20/17 (85)	< 20	555	178	Federal District	2003–2005	Caldas et al., 2007
Corn flakes	20/8 (40)	< 20	906	127	Federal District	2003–2005	Caldas et al., 2007
Popcorn	24/22 (91.7)	< 20	2100	664	Federal District	2003–2005	Caldas et al., 2007
Sweet corn	29/6 (20.7)	< 20	1440	272	Federal District	2003–2005	Caldas et al., 2007
Corn flour (wet milling)	21/21 (100)	70	2050	653	Federal District	2003–2005	Caldas et al., 2007
Corn flour (dry milling)	21/21 (100)	337	2380	1090	Federal District	2003–2005	Caldas et al., 2007
Unprocessed corn	435/435 (100)	30	18,160	1460	Paraná	2004	Ono et al., 2008
Unprocessed corn	245/245 (100)	30	11,210	1233	Paraná	2004	Silva et al., 2008
Unprocessed corn	150/146 (97.3)	< 27.5	18,160	1335	Paraná	2004	Moreno et al., 2009
Unprocessed corn	50/50 (100)	91	9670	2810	São Paulo	2005	Rocha et al., 2009
Unprocessed corn	50/50 (100)	15	6270	720	Rio Grande do Sul	2005	Rocha et al., 2009
Unprocessed corn	50/50 (100)	15	9420	2750	Bahia	2005	Rocha et al., 2009
Unprocessed corn	50/46 (92)	< 15	8440	730	Mato Grosso	2005	Rocha et al., 2009
Unprocessed corn	80/80 (100)	130	19,520	6970	Paraná	2006	Ono et al., 2011
Unprocessed corn	119/119 (100)	41	8760	na	Paraná	2006	Souza et al., 2013
Corn for animal feed	36/36 (100)	58	1592	na	Paraná	2006	Souza et al., 2013
Unprocessed corn	16/16 (100)	3700	7750	6290	Paraná	2007	Ono et al., 2011
Unprocessed corn	52/22 (42.3)	< 6.6	4305	977	Santa Catarina	2007	Scussel et al., 2014
multiple corn based products	100/82 (82)	< 43.1	4348	457	Paraná	2007–2010	Martins et al., 2012
Unprocessed corn	52/12 (23.2)	< 6.6	1510	432	Santa Catarina	2008	Scussel et al., 2014
Unprocessed corn	16/7 (43.8)	< 78	2340	1280	Rio Grande do Sul	2009	Stumpf et al., 2013
Unprocessed corn	40/40 (100)	230	6.450	2338	Minas Gerais	2009	Queiroz et al., 2012
Unprocessed corn	57/25 (43.8)	< 6.6	7832	2397	Santa Catarina	2009	Scussel et al., 2014
Unprocessed corn	40/40 (100)	1096.25	5000	2338.5	Minas Gerais	2009	Pimentel et al., 2018
Unprocessed corn	21/21 (100)	1613.33	4216.67	2738.6	Minas Gerais	2010	Pimentel et al., 2018
Unprocessed corn	13/10 (77)	< 78	2840	1080	Rio Grande do Sul	2010	Stumpf et al., 2013
Unprocessed corn	11/4 (36.4)	< 6.6	3000	1081	Santa Catarina	2010	Scussel et al., 2014
Unprocessed corn	59/18 (30.5)	< 500	1800	1061	Santa Catarina	2010	Horn et al., 2014
Unprocessed corn	65/18 (27.7)	< 500	3500	1247	Rio Grande do Sul	2010	Horn et al., 2014
Unprocessed corn	88/10 (11.4)	< 500	2000	1300	Paraná	2010	Horn et al., 2014
Unprocessed corn	17/6 (35.3)	< 6.6	2000	947	Santa Catarina	2011	Scussel et al., 2014
Unprocessed corn	90/24 (12.8)	< 500	1600	833.3	Santa Catarina	2011	Horn et al., 2014
Unprocessed corn	96/33 (34.4)	< 500	2600	824.2	Rio Grande do Sul	2011	Horn et al., 2014
Unprocessed corn	131/41 (31.3)	< 500	2900	832	Paraná	2011	Horn et al., 2014
Corn meal	32/25 (78.1)	< 30	1208.6	476.6	São Paulo	2011–2012	Bordin et al., 2014

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Table 1 (*continued*)

Sample type	Number of samples/ positive samples (% of positive samples)	Fumonisin levels (FB1 or FB1 + FB2, when available)			Location (State)	Year of sampling	Reference
		Minimum levels (µg/kg)	Maximum levels (µg/kg)	Mean levels [a] (µg/kg)			
Corn flour	25/19 (76)	< 30	558.6	247	São Paulo	2011–2012	Bordin et al., 2014
Popcorn	39/32 (82.1)	< 30	1127.3	278.3	São Paulo	2011–2012	Bordin et al., 2014
Polenta	2/2 (100)	149	214.2	181.6	São Paulo	2011–2012	Bordin et al., 2014
Unprocessed corn	21/7 (33.3)	< 6.6	7.832	1402	Santa Catarina	2012	Scussel et al., 2014
Unprocessed corn	32/32 (100)	400	9100	3430	Paraná	2012	Silva et al., 2017
Unprocessed corn	109/14 (12.8)	< 500	1200	750	Santa Catarina	2012	Horn et al., 2014
Unprocessed corn	111/21 (18.9)	< 500	4400	1580	Rio Grande do Sul	2012	Horn et al., 2014
Unprocessed corn	257/48 (18.7)	< 500	3000	840	Paraná	2012	Horn et al., 2014
Unprocessed corn	57/57 (100)	63.8	66.274	3153	Paraná	2012–2013	Oliveira et al., 2017
Unprocessed corn	40/40 (100)	62.4	10,800	2204	Santa Catarina	2012–2013	Oliveira et al., 2017
Unprocessed corn	51/51 (100)	120.5	24,581	2726	Rio Grande do Sul	2012–2013	Oliveira et al., 2017
Unprocessed corn	15/12 (80)	< 2.5	1732	289	Santa Catarina	2013	Savi et al., 2016
Corn grits	15/15 (100)	88	2727	719	Santa Catarina	2013	Savi et al., 2016
Corn flour	15/15 (100)	15	1542	415	Santa Catarina	2013	Savi et al., 2016
Corn meal	15/8 (53)	< 2.5	5439	1395	Santa Catarina	2013	Savi et al., 2016
Cereal mixture	105/88 (83.8)	< 2	1876	137.8	Minas Gerais, Paraná, Rio Grande do Sul, Santa Catarina and São Paulo	2013	Peluque et al., 2013
Unprocessed corn	160/ 157 (98)	< 15	9419	1378.8	São Paulo	2014	Barroso et al., 2017
Unprocessed corn	20 /16 (80)	< 27.5	1441.2	481.41	Paraná	2014	Bordini et al., 2017
Corn meal	20/20 (100)	79.38	287.41	168.24	Paraná	2014	Bordini et al., 2017
Corn grits	20/10 (50)	< 27.5	208.34	89.2	Paraná	2014	Bordini et al., 2017
Unprocessed corn	20/20 (100)	303.5	1865.3	1308.8	Paraná	2015	Bordini et al., 2017
Corn meal	20/9 (45)	< 27.5	389.4	218.3	Paraná	2015	Bordini et al., 2017
Corn grits	20/9 (45)	< 27.5	78.3	na	Paraná	2015	Bordini et al., 2017
Corn flakes	25/0	< 3.37	< 3.37	< 3.37	São Paulo	2015	Andrade et al., 2018
Popcorn	25/24 (96)	< 3.37	3170	592	São Paulo	2015	Andrade et al., 2018
Unprocessed corn	205/205 (100)	190	7930	3700	Piauí	2015	Silva et al., 2022
Pamonha	52/52 (100)	54.7	1195	146.1	Santa Catarina	2015–2016	Silva et al., 2017
Unprocessed corn	80/80 (100)	121	2730	1026	Paraná	2015–2016	Bordini et al., 2019
Corn meal	80/60 (75)	< 27.5	569	191	Paraná	2015–2016	Bordini et al., 2019
Corn grits	80/56 (70)	< 27.5	256	70.6	Paraná	2015–2016	Bordini et al., 2019
Maize flour/meal	248/237 (95.6)	< 3.37	19,087	776.1	Federal District	2015–2016	Andrade et al., 2020
Popcorn	13/13 (100)	28.3	1042.2	294.9	Federal District	2015–2016	Andrade et al., 2020
Maize starch	6/6 (100)	31	32.8	31.7	Federal District	2015–2016	Andrade et al., 2020
Maize grits	3/3 (100)	68.5	136.3	113.7	Federal District	2015–2016	Andrade et al., 2020
Maize snacks	18/18 (100)	2.9	303.5	83.2	Federal District	2015–2016	Andrade et al., 2020
Maize pasta	1/1 (100)	59	59	59	Federal District	2015–2016	Andrade et al., 2020
Breakfast cereals	10/10 (100)	2.7	551.8	72.8	Federal District	2015–2016	Andrade et al., 2020
Unprocessed corn	12/8 (66.7)	na	6480	1588.9	Paraná and Mato Grosso	2015–2016	Gasperini et al., 2021
Popcorn	50/50 (100)	15.1	1246.7	255.7	Rio de Janeiro	2016–2017	Matos et al., 2024
Corn meal	50/50 (100)	39.2	2158.2	550.9	Rio de Janeiro	2016–2017	Matos et al., 2024

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Table 1 (*continued*)

Sample type	Number of samples/ positive samples (% of positive samples)	Fumonisin levels (FB1 or FB1 + FB2, when available) Minimum levels (μg/kg)	Maximum levels (μg/kg)	Mean levels [a] (μg/kg)	Location (State)	Year of sampling	Reference
Precooked corn flakes	49/49 (100)	12	990.5	267.6	Rio de Janeiro	2016–2017	Matos et al., 2024
Roasted corn flour	18/18 (100)	42.5	607.4	198.1	Rio de Janeiro	2016–2017	Matos et al., 2024
Corn grits	21/21 (100)	10.9	465.9	162.5	Rio de Janeiro	2016–2017	Matos et al., 2024
White corn grits	15/15 (100)	7.2	160.3	63.9	Rio de Janeiro	2016–2017	Matos et al., 2024
Curau	9/9 (100)	22	843.3	292.7	Rio de Janeiro	2016–2017	Matos et al., 2024
Corn for animal feed	241/207 (85.9)	< 200	31,420	na	Multiple States (contamination was not separated by region)	2017–2021	Biscoto et al., 2022
Corn meal	4/4 (100)	69.44	131.92	103.1	São Paulo	2018	Franco et al., 2018
Corn flour	2/2 (100)	7.11	48.78	27.9	São Paulo	2018	Franco et al., 2018
Corn meal/flour	26/26 (100)	2.9	1500	na	Santa Catarina and São Paulo	2019	Franco et al., 2019
Corn for animal feed	45/45 (100)	17	54,000	na	Santa Catarina and São Paulo	2019	Franco et al., 2019
Unprocessed corn	234/107 (45.7)	< 10	4810	270	Paraná	2020	Simões et al., 2023
Flaked flour	23/4 (17)	< 70	480	190	São Paulo	2020–2021	Gomes et al., 2024
Corn meal	34/16 (47)	< 70	942.4	220.1	São Paulo	2020–2021	Gomes et al., 2024
Corn flour	33/9 (54.3)	< 70	375	216.7	São Paulo	2020–2021	Gomes et al., 2024
Corn flaked	2/2 (100)	80.5	144.7	112.6	São Paulo	2020–2021	Gomes et al., 2024
Corn flakes	3/1 (33.3)	< 70	141.4	141.4	São Paulo	2020–2021	Gomes et al., 2024
Corn cream	1/1 (100)	< 70	965.1	965.1	São Paulo	2020–2021	Gomes et al., 2024
Small hominy	2/0	< 70	nd	nd	São Paulo	2020–2021	Gomes et al., 2024
White hominy	9/1 (11)	< 70	305.6	305.6	São Paulo	2020–2021	Gomes et al., 2024
Yellow hominy	3/0	< 70	< 70	< 70	São Paulo	2020–2021	Gomes et al., 2024
Popcorn	30/11 (36.7)	< 70	575.6	281.2	São Paulo	2020–2021	Gomes et al., 2024
Corn-based products	11/11 (100)	206	18,801	na	São Paulo	2021	Franco & Oliveira, 2022
Unprocessed corn	216/149 (68.9)	< 10	3740	446	Paraná	2021	Simões et al., 2023
Corn-based products	32/27 (86)	< 0.9	1534.89	na	São Paulo	2022	Ali et al., 2024
Corn meal	50/22 (44)	< 32.16	1460.76	196.3	Minas Gerais	na	Paschoal et al., 2017 [d]
Unprocessed corn	76/46 (60.5)	< 2.5	3303	585	Rondônia	na	Valmorbida et al., 2017 [d]
Mean (1991–2010) [e]		684.6	11826.1	2692.1			
Median (1991–2010) [e]		157	6450	1460			
Mean (2011–2022) [e]		76.5	5095.9	685.4			
Median (2011–2022) [e]		54.7	1227.7	290.9			

[a] Mean levels and [b] Limit of detection (LOD) of the method as indicated in the literature cited; [c] na: data not available in the referenced studies; [d] The mentioned studies were excluded from the mean and median fumonisin level calculations due to a lack of reported sampling years; [e] Mean and median levels were calculated using available literature data, considering exclusively samples that exceeded the reported LOD in the cited studies.

during 2016–2022 to 6,002.6 μg/kg during 1991–1995. In contrast, the levels of fumonisins in maize by-products ranged between 228.2 μg/kg from 2016 to 2022 and 1,360.7 μg/kg from 1996 to 2000. The decline in contamination levels for unprocessed maize and its by-products was also noticeable across the five-year time frames (Table 1, Fig. 3).

It is worth emphasizing that most studies (> 85 %) reported in this review have been conducted in Brazil's Southeast and South regions, lacking documented research from the Central, Northern, and Northeastern areas. Consequently, investigating the occurrence of fumonisins in maize and its by-products in these underrepresented areas is warranted, especially because Mato Grosso is a critical maize-producing state, and there is a growing trend of cultivation in the Northern and Northeastern regions of Brazil.

Worldwide literature data also indicates a high incidence of fumonisins in maize. Farhadi et al. (2021) conducted a systematic review covering fumonisins in cereal-based foods from 1991 to 2020. Mean

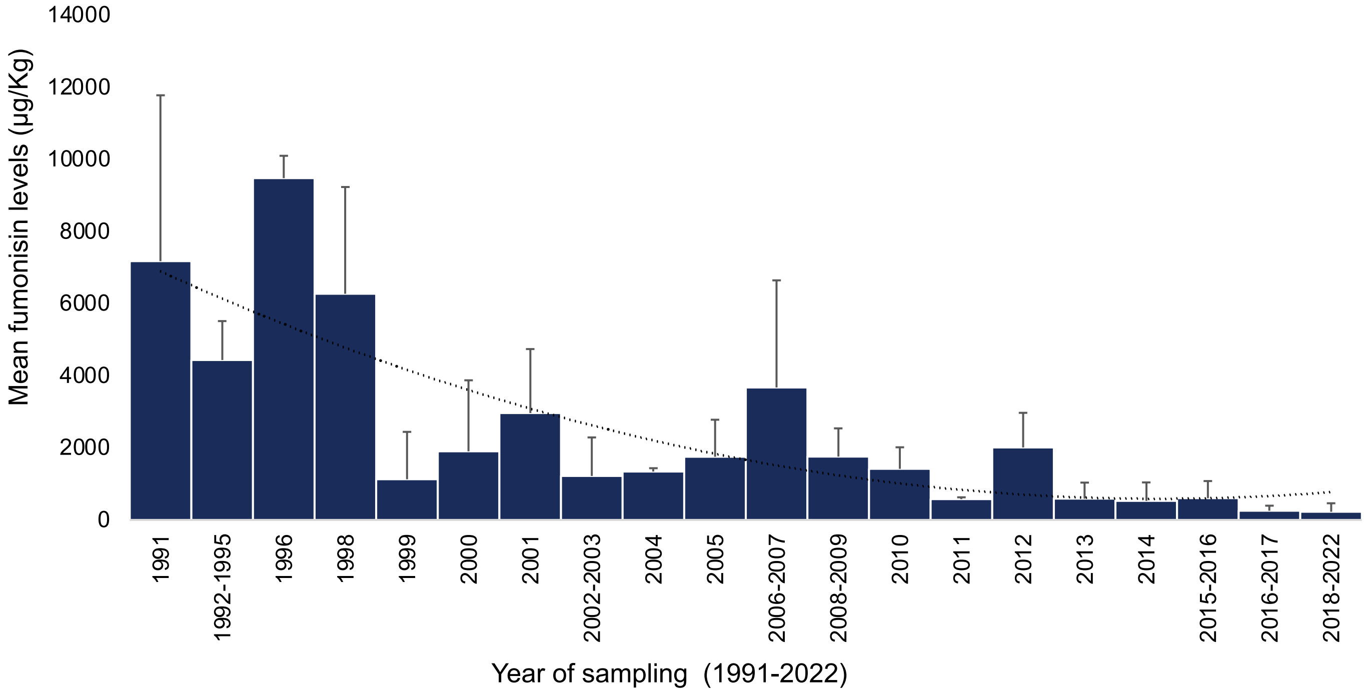

Fig. 2. Mean fumonisin levels (µg/kg) in Brazilian maize and its by-products from 1991 to 2022. Columns with bars represent the mean fumonisin levels (± standard deviation) based on data from Table 1, considering the mean levels reported in the cited studies when available. Studies lacking mean level data were excluded from the dataset.

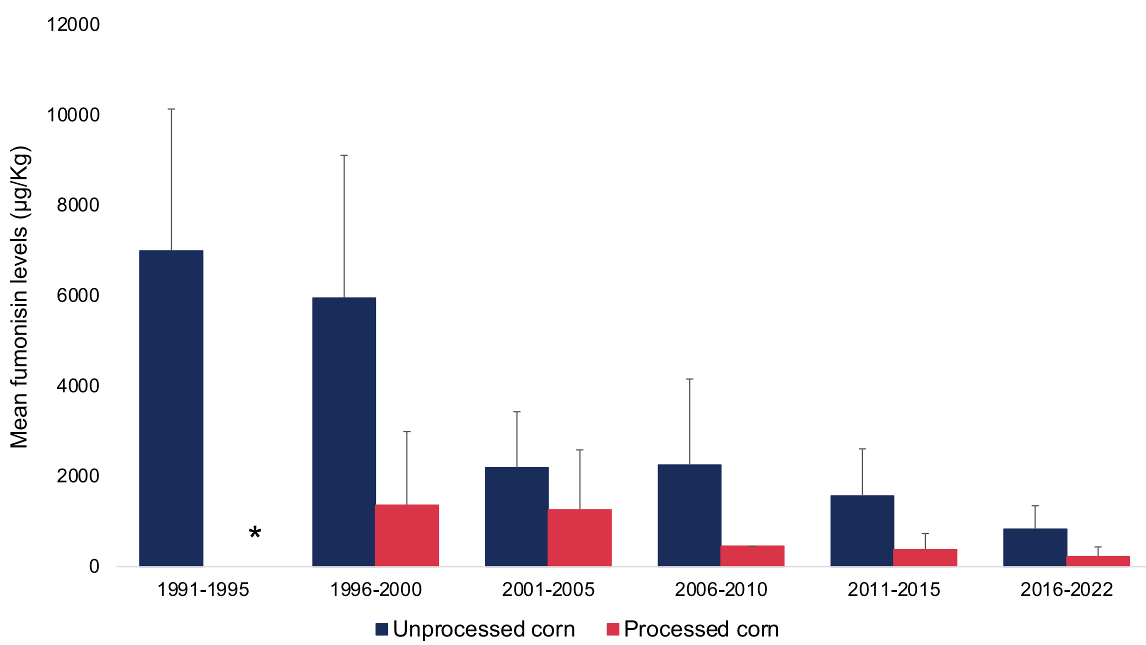

Fig. 3. Mean fumonisin levels (µg/kg) in Brazilian unprocessed and processed maize across successive five-year periods from 1991 to 2022. Columns with bars represent the mean fumonisin levels (± standard deviation) based on data from Table 1, considering the mean levels reported in the cited studies when available. Studies lacking mean level data were excluded from the dataset. * No fumonisin data for processed maize was reported between 1991 and 1995.

fumonisin levels ranged from 96.56 µg/kg to 251.84 µg/kg, with maize-based products showing higher concentrations and Bulgaria presenting higher occurrence and levels, reaching 734.2 µg/kg. Conversely, Bryła et al. (2022) reported higher levels of fumonisins in maize, especially in Brazil and North America, reaching 45,145.82 µg/kg for only FB1.

In another study, mycotoxin occurrence in maize and by-products was reported worldwide from 2002 to 2020. High fumonisin occurrence was observed in North, Central, and South America, Asia, the Middle East, and North Africa, particularly in areas conducive to *Fusarium* ear rot. The highest fumonisin concentrations were detected in unprocessed maize, particularly used for animal feed, with average FB1 levels reaching 44,460 µg/kg in maize ears in Poland (Gromadzka et al., 2016).

5. The establishment of Brazilian MLs for fumonisins in maize

Maximum levels for fumonisins in maize serve as set thresholds for acceptable concentrations of these mycotoxins, which are produced primarily by members of the FFSC and can contaminate maize and other grains. Due to their health risks, including cancer, liver damage, and neurotoxicity, particularly in livestock, governments and international organizations, such as the Codex Alimentarius commissionthrough its CCCF, established MLs to ensure that maize-based foods remain within safe limits.

Regulatory authorities enforce these MLs through monitoring and testing programs. If fumonisin levels exceed the maximum allowable limits, regulatory actions may be taken, such as recalling contaminated products from the market or imposing penalties on producers or suppliers.

Occurrence data strongly influence the establishment of MLs for tolerated mycotoxins in food and feed, as it provides information on the exposure of consumers to mycotoxins. Together with toxicological studies, this data aids regulatory authorities in conducting risk assessments to evaluate health risks associated with mycotoxin exposure. Based on these findings, authorities can establish MLs that protect consumers' health while considering the levels of mycotoxins commonly found in food and feed. Additionally, it supports the development of international standards (e.g., CXC 51–2003) for member countries, allowing the harmonization of regulatory frameworks. Finally, authorities use this data to monitor compliance with established MLs, assess the effectiveness of control measures, and, if needed, adjust the MLs in response to emerging risks or changes in contamination levels.

Before 2011, Brazil's regulations on mycotoxins were limited and did not include MLs for fumonisins in food products. At that time, the Brazilian delegation's discussions with the CCCF influenced the necessity for revising the national regulations, as Brazil was experiencing rejection of certain exported food products, which included maize, due to fumonisin contamination; this led to an influx of contaminated foods within Brazilian markets (Taniwaki et al., 2018).

Particularly concerning fumonisin contamination in maize, the rejection of exported lots due to high levels of fumonisins could be an issue, as Brazil is a major producer and exporter of this commodity. To address this, ANVISA formally began collecting national-level occurrence data on fumonisin contamination and initiated efforts to establish MLs. These initiatives also included enhancing producers' adoption of GAP and GMP to reduce fumonisin levels in maize and discussions within the national subcommittee and with stakeholders involved. Engaging industry players and farmers was important as their products would need to comply with the proposed regulations. Government agencies were also responsible for developing policies for subsequent monitoring, while academia contributed by providing data on fumonisin contamination and innovations for its control.

Although the initial proposed MLs were based on EU regulations, ANVISA later adjusted them, following extensive discussions with subcommittee Members and stakeholders. Embracing an innovative strategy, ANVISA adopted relatively high MLs and followed a phased approach, progressively reducing the acceptable levels each year (Table 3). This novel strategy, combined with knowledge of the CXC 51–2003 content among stakeholders, aided in reducing fumonisin levels over time. Research findings post-2011 indicated a substantial decline in contamination levels, generally aligning with international standards (Table 1).

6. The impact of Brazil's compliance to CXC 51–2003 and the MLs for fumonisins in Brazilian maize

The CXC 51–2003 provides information for mycotoxin management based on GAP and GMP that can be applied to numerous food and feed chains. ANVISAs extensive efforts with various stakeholders resulted in enhanced awareness at the national level regarding the adoption of the directives outlined in CXC 51–2003. ANVISA's establishment of MLs for fumonisins also triggered a series of favorable outcomes, leading to decreased fumonisin contamination in maize and its by-products during the last 30 years.

Over the past decade, Brazil has significantly expanded its maize exports, ensuring its position as the world's second-largest exporter. This growth can be attributed to coordinated efforts, such as government investments and optimizing multiple crop seasons (CONAB, 2021; CONAB, 2024b; CONAB, 2024c). The initiatives to reduce fumonisin contamination also played an important role in this progress. For instance, research conducted by institutions such as the Brazilian Agricultural Research Corporation (EMBRAPA), Agronomical Institute of Campinas (IAC), and other research resulted in the recognition of maize cultivars resistant to fungi, including *F. verticillioides*, thereby reducing fumonisin contamination during preharvest (Almeida et al., 2023; Costa et al., 2010). Enhanced knowledge of GAP and GMP, along with the continuous efforts of MAPA to monitor mycotoxins in food and that farmers comply with the guidelines outlined in CXC 51–2003, further contributed to these advancements.

The increased awareness among producers led to a significant change in the maize production practices during pre and postharvest. This included the selection of cultivars resistant to drought and insect infestation and postharvest interventions such as measuring fumonisin levels in grains, drying, cleaning, and sorting, with studies particularly showing that sorting can reduce significantly fumonisin levels in grains (Pitt et al., 2012).

The collective impact of these measures has not only improved maize quality but also boosted overall productivity. Supplementary Figure 1 shows an increased maize export value (US$) in Brazil and a reduction of fumonisin contamination based on published data during the last 30 years. We emphasize that the export growth is due to various national initiatives, including the production of maize throughout the year, an expansion in cultivated areas, investments in new cultivars, overall improvements in quality, and other factors. Nevertheless, reducing fumonisin contamination in maize enhanced product quality and strengthened international market confidence and acceptance (Costa et al., 2010; Evangelista et al., 2023).

Although a significant portion of Brazilian maize production is intended for export, a substantial amount is also consumed nationally (IBGE, 2022). Therefore, it is informative to monitor the occurrence of fumonisins in maize and evaluate the risk associated with its consumption (Andrade et al., 2020). In this respect, we calculated the probable daily intake (PDI) of fumonisins based on occurrence data reported in Brazil from 1991 to 2022 and maize consumption. The average weight of Brazilian men (70 kg) and women (60 kg), along with average daily maize consumption of 18.1 g (men) and 15.2 g (women), were considered (IBGE, 2018; 2022); the estimated results were obtained according to the method described by Franco and Oliveira (2022) and expressed as μg/kg of body weight (bw)/day.

Table 2 presents the estimated PDI across five-year intervals from 1991 to 2022, demonstrating a reduction in men's and women's fumonisin exposure through maize consumption over the years. In the initial period (1991–1995), the PDI was 1.236 μg/kg bw/day for Brazilian men and 1.211 μg/kg bw/day for women, surpassing the tolerable daily intake (TDI) threshold of 1 μg/kg bw/day set by ESFA (EFSA, 2018). Conversely, in the most recent period (2016–2022), the average PDI decreased to 0.054 μg/kg bw/day for men and 0.053 μg/kg bw/day for women, representing only 5.3 % of the fumonisins' TDI limit (EFSA, 2018). While earlier periods exceeded safe limits set by EFSA, recent data highlights the progress in reducing fumonisin intake and improving national food safety standards.

This data represents a collection of information available in the literature, indicating a positive trend in reducing fumonisin levels in maize and its by-products and the population's exposure to fumonisins. Nevertheless, obtaining occurrence data and monitoring efforts remain essential for risk assessment purposes, ensuring that any fluctuations in

Table 2
Probable daily intake (PDI) of fumonisins based on occurrence data reported in Brazil from 1991 to 2022. It was considered an average weight of 70 kg (men) and 60 kg (women); and an average daily corn consumption of 18.1 g (men) and 15.2 g (women); only fumonisin levels reported in maize and maize products intended for human consumption were included; PDI results were estimated according to Franco and Oliveira (2022).

PDI (μg/kg of bw/day)						
Year of sampling	**1991–1995**	**1996–2000**	**2001–2005**	**2006–2010**	**2011–2015**	**2016–2022**
Men	1,236	0,569	0,342	0,331	0,213	0,054
Women	1,211	0,557	0,335	0,324	0,209	0,053

PDI: probable daily intake; bw: body weight.

Table 3
Progression of the maximum levels (MLs) of fumonisins allowed by the Brazilian Surveillance Agency (ANVISA) from 2011 to 2022.

Food product	MLs (μg/kg) for FB1 + FB2						
	2011	**2012**	**2014**	**2016**	**2017**	**2021**	**2022**
Popcorn	2000	2000	2000	2000	2000	2000	2000
Corn flour, corn cream, cornflakes cornmeal, canjica, canjiquinha	–	2500	2500	1500	1500	1500	1500
Corn kernels for further processing	–	–	5000	5000	5000	5000	5000
Cornstarch and other corn-based products	–	–	–	1000	1000	1000	1000
Corn-based baby food	–	–	–	–	–	200	200
References	Brazil, 2011				Brazil, 2017	Brazil, 2021	Brazil, 2022

MLs: Maximum levels; FB1: fumonisin B1; FB2: fumonisin B2.

fumonisin contamination levels are identified and properly addressed.

Moreover, this review highlighted the successful outcomes of collaborative initiatives conducted in Brazil, serving as an example that other countries could employ. Nevertheless, the occurrence data primarily focused on the Southeast and South regions, emphasizing a need for broader sampling across Brazil's Midwest, North, and Northeast areas.

Given Brazil's vast size and the diversity of agricultural practices (i. e., small-scale farming versus industrial agriculture), disparities in enforcement and compliance can be challenging. For instance, remote regions in the Midwest, North, and Northeast and small-scale farmers may present limited resources and infrastructure, resulting in different levels of compliance with regulations. Thus, data on fumonisin occurrence in these groups is warranted not only for monitoring purposes but also for conducting a more comprehensive risk assessment with the data gathered.

In this regard, active collaboration among academia, industry, and regulatory bodies is essential for collecting and analyzing data, as well as raising awareness of the health and economic risks associated with mycotoxin contamination across the country; providing educational support for the understanding of CXC 51-2003, especially among small-scale farmers, is relevant to enhancing food security initiatives.

Furthermore, based on the achievements of these collaborative efforts aimed at reducing fumonisin levels, we underscore the importance of submitting occurrence data to the scientific committees of the WHO and FAO, such as JECFA, to facilitate a thorough global risk assessment. The outcomes from these efforts enable countries to reevaluate their practices and strategies for reducing mycotoxin contamination and support the establishment of fair MLs that reflect national and international needs, balancing food safety and trade.

7. Conclusions and recommendations

The regulatory initiatives led by ANVISA, thanks to the Codex texts developed by CCCF, and together with national stakeholders, have significantly impacted fumonisin contamination in Brazilian maize over the last three decades. Increasing the awareness of the Codex texts, adapting to the national context the principles detailed in CXC 51-2003 and adopting MLs for fumonisins in maize have not only contributed to reducing contamination but have also strengthened food safety protocols and ultimately improved Brazilian maize exports. In addition, the data indicated a reduction in fumonisin exposure by the Brazilian population during the last years.

While decreasing fumonisin contamination is a significant achievement, continuing these efforts is necessary. We stress the importance of collecting samples from underrepresented regions and small-scale farmers to gain a more comprehensive understanding of fumonisin contamination nationwide. Establishing ongoing monitoring and evaluation mechanisms is equally important to ensure improvement and adherence to Codex texts while addressing the gaps in awareness among stakeholders.

We also encourage collaborative initiatives among academia, industry, and regulatory authorities to sustain current reduction efforts. The continuous dialogue among these institutions is important for developing unified strategies to address the evolving challenges of mycotoxin contamination in maize production.

Finally, addressing mycotoxin contamination requires a global collaborative approach, which includes sharing occurrence data at the international level, ensuring that more representative samples are considered during risk assessments. This not only protects consumers' health but also promotes fair trade practices, establishing equitable MLs and aiding economic growth worldwide.

CRediT authorship contribution statement

Liliana de Oliveira Rocha: . **Marta Hiromi Taniwaki:** Writing – review & editing. **Michael Ennis:** Writing – review & editing. **Ligia Lindner Schreiner:** Writing – review & editing. **Farid El Haffar:** Writing – review & editing, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodres.2024.115280.

Data availability

No data was used for the research described in the article.

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