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EDITED BY
Rohit Mahar,
Hemwati Nandan Bahuguna Garhwal
University, India

REVIEWED BY
Florin Oancea,
National Institute for Research & Development
in Chemistry and Petrochemistry (ICECHIM),
Romania

*CORRESPONDENCE
Claudia Foerster,
claudia.foerster@uoh.cl

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A mini review of mycotoxin's occurrence in food in South America in the last 5 years: research gaps and challenges in a climate change era

Claudia Foerster[1]*, Andrea Müller-Sepúlveda[2], Marina Venturini Copetti[3], Andrea Alejandra Arrúa[4], Liliam Monsalve[1], María Laura Ramirez[5] and Adriana M. Torres[5]

[1]Mycotoxin Research Laboratory, Institute of Agri-Food, Animal and Environmental Sciences (ICA3), Universidad de O'Higgins, San Fernando, Chile, [2]Pharmacology Laboratory, Institute of Agri-Food, Animal and Environmental Sciences (ICA3), Universidad de O'Higgins, San Fernando, Chile, [3]Laboratory of Food Mycology (LAMA), Department of Food Technology and Science, Federal University of Santa Maria, Santa Maria, RS, Brazil, [4]Laboratory of Biotechnology, Centro Multidisciplinario de Investigaciones Tecnológicas CEMIT, UNA, Universidad Nacional de Asunción, San Lorenzo, Paraguay, [5]Laboratory of Mycology, Instituto de Investigación en Micología y Micotoxicología (IMICO), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Universidad Nacional de Río Cuarto, Río Cuarto, Argentina

Mycotoxins are natural metabolites produced by species of filamentous fungi belonging mainly to the genera *Aspergillus, Fusarium, Penicillium,* and *Alternaria*, which can grow in various crops and foodstuffs. The South American climate is diverse, varying from tropical, temperate, and arid to cold, ideal for the growth of different types of fungi and mycotoxin production. This mini review aimed to describe the natural occurrence of mycotoxin in food in South America from 2018 to 2023, identifying research gaps and challenges in an era of climate change. We analyzed 53 studies, 21 from Brazil. Most of the mycotoxins analyzed in South America were the traditional and regulated mycotoxins, with variable occurrences depending on the region, climatic conditions, and methodology used. Emerging and modified mycotoxins have only been studied in Argentina and Brazil, where some studies have shown high occurrences. Given this, it is essential to strengthen food safety laboratories and surveillance capabilities and establish early warning systems. It is also essential to continue working to raise awareness of mycotoxins as a public health issue and to study and prevent the impact of climate change on soil microbial population, the new prevalence of fungi, and the profile of toxigenic species. An effective connection and collaboration between disciplines and sectors in different countries is needed to meet this research challenge.

KEYWORDS

mycotoxins, occurrence, natural contamination, foodstuffs, emerging mycotoxins, human consumption, South America

1 Introduction

South America (14.6048°S, 59.0625°W) is a continent that has an area of 17,840,000 square kilometers (6,890,000 sq mi). Consistent with its size, it extends from a broad equatorial zone in the north to a narrow sub-Arctic zone in the south and includes twelve sovereign states: Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, and Venezuela. The South American climate varies from tropical to temperate, arid, and cold (Garreaud et al., 2009). This variable climate is ideal for different types of fungal growth and mycotoxin production. Mycotoxins are secondary metabolites produced by filamentous fungal species mainly belonging to *Aspergillus, Fusarium, Penicillium*, and *Alternaria*, which can grow in various crops and foodstuffs. Mycotoxins have a particular structural and chemical characteristic, which determine their biological and toxicological properties. Between 300 and 400 types are recognized, and about a dozen of them are considered important threats to human or animal health (Bennett and Klitch, 2003). Some mycotoxins stand out for their high toxicity, such as aflatoxins, which are among the most potent natural hepatocarcinogens known to date. Others, like ochratoxin A (OTA) and citrinin (CIT), can affect the kidney, the nervous system (patulin, PAT), or the reproductive system (zearalenone, ZEN). Some have multiple toxic effects in humans and animals like deoxynivalenol (DON), nivalenol (NIV), and T-2 toxin are most likely associated with the high incidence of esophageal cancer in specific populations like fumonisins B_1 and B_2 (FB_1- FB_2) (International Agency for Research on Cancer, 2012). The latest mycotoxins are regulated in many countries of South America and the rest of the world and have been widely studied (van Egmond et al., 2007). However, it is also essential to study emerging mycotoxins, which are increasing in incidence and are defined as mycotoxins that are neither routinely determined nor have legislative regulation (Vaclavikova et al., 2013). Some of the emerging mycotoxins of interest are *Fusarium* metabolites fusaproliferin (FP), beauvericin (BEA), enniatins (ENNs), and moniliformin (MON), fusaric acid (FA), culmorin (CUL), and butenolide (BUT), the *Aspergillus* metabolites sterigmatocystin (STE) and emodin (EMO), the *Penicillium* metabolite mycophenolic acid (MPA), and the *Alternaria* metabolites alternariol (AOH), alternariol monomethyl ether (AME), and tenuazonic acid (TeA) (Gruber-Dorninger et al., 2017).

South America's economy is centered on the export of natural resources, including diverse food products prone to mycotoxins, like nuts, coffee, and cacao, and industrial crops such as corn, wheat, soybeans, rice, quinoa, and cotton (Cardenas and Orozco, 2022). Likewise, South America is experiencing the effects of climate change, including extreme weather events and changes in temperature and precipitation patterns (Fernandez-Guzman et al., 2023). Climate change is expected to increase and modify mycotoxin contamination. Research has demonstrated that only a slight elevation of CO_2 levels will stimulate the growth of mycotoxin-producing fungi. There is an increased risk for mycotoxin contamination of corn, wheat, and other small grain species. In a changing climate, mycotoxins will increase and contaminate new crops and new geographical areas (Zingales et al., 2022).

This mini review aimed to describe the natural occurrence of mycotoxin in food in South America over the last 5 years (2018–2023) and identify the research gaps and challenges in a climate change era.

2 Occurrence of mycotoxins in food by country

Bolivia, Guyana, Suriname, French Guiana, Trinidad and Tobago, and Venezuela have not reported mycotoxin data in food from 2018 to 2023. The collected data from the rest of the countries ($n = 53$) are summarized in Table 1. Details of the studies regarding occurrence, levels, and methodology are collected in the Supplementary Table S1.

2.1 Argentina

This country has had eight studies in the last 5 years. Corn was analyzed for DON and their metabolites 3-ADON, 15-ADON, also FB_1, FB_2, NIV, and ZEN, finding DON and 3-ADON in 90% and 40% of the samples, respectively (Castañares et al., 2019). Other cereals analyzed were malting barley, which found 16% DON and 22% NIV (Nogueira et al., 2018). In wheat: AOH, AME, and TeA were found with occurrences of 19%, 38%, and 50–62%, respectively (Romero Bernal et al., 2019), and FB_1 and FB_2 with occurrences ranging from 50 to 100% in wheat flour (Cendoya et al., 2019). Regarding fruits, apples, tomatoes, and grapes have been analyzed. Interestingly, apple baby food ($n = 20$) was found to have AOH in 35%, AME in 100%, TeA in 70%, and tentoxin (TEN) in 95% of the samples, while altertoxin-I (ATX-I) and altenuene (ALT) were not found (Pavicich et al., 2023). This is important as emerging mycotoxins are not regulated in Argentina or the rest of South America. Regarding tomatoes, occurrences of AOH in 18%, AME in 8%, TeA in 21%, TEN in 13%, ATX-Iin 5%, and ALT in 8% of the samples (Maldonado Haro et al., 2023). Grapes for winemaking were found to have TeA in 16% of the cases, ranging from 77 to 133 ng/g (Prendes et al., 2018). Finally, milk samples were found (78%) with AFM_1 ranging from 3 to 64 ng/mL (Costamagna et al., 2019).

2.2 Brazil

Brazil is the country with the most studies made in the period ($n = 21$) on all types of foods. The first study analyzed aflatoxins and OTA in various spices, finding aflatoxins in fennel at 27% and 20% in rosemary (Valle Garcia et al., 2018). Also, in spices, Persson da Silva et al. (2021) found OTA in 55% of black pepper samples. Regarding nuts, Silva et al. (2018) found aflatoxins in 64% of peanut samples ($n = 42$) and 28% in blanched peanuts ($n = 18$). No aflatoxins were found in Pecan nuts ($n = 52$) (Valle Garcia et al., 2019), while Kluczkovski et al. (2022) found 28% of aflatoxin contamination in Brazil nut oil ($n = 25$). Milk and milk products were also analyzed for different mycotoxins, most frequently AFM_1. This mycotoxin was found in raw milk (12.5%), pasteurized milk (36%), UHT milk (48%), Minas cheese (47%), and yogurt (25%) (Corassin et al., 2022); was also present in all samples ($n = 7$) of artisanal mozzarella, manufactured mozzarella, artisanal rennet and manufactured rennet (Costa da Silva et al., 2021), and goat milk ($n = 108$) (de Matos et al., 2021). Frey et al. (2021) analyzed AFM_1, DOM-1, OTA, FB_1, FB_2, alpha-zearalenol, and beta-zearalenol in different types of milk, finding occurrences from 9% to 25%, 8.8% to 9.4%, 18.7% to 25%, 12.5% to 50%, 4.4% to 25%, 25% to 57.4%, and 25% to 50%, respectively. Most of the studies have been done on cereals and cereal products. Regarding breakfast and infant cereals, Mallmann

TABLE 1 Studies of mycotoxins natural contamination in food for human consumption, with data collected 2018–2023 in countries of South America.

Country	Number studies	Most analyzed mycotoxin	Most analyzed food item	Higher occurrence	More used methodology	Regulation in mycotoxins in food (internal)
Argentina	8	*Fusarium* and *Alternaria* mycotoxins	Malting-barley	AME in apple infant food and fumonisin B_2 in wheat flour (100%)	Chromatography (MS, DAD, UV)	Yes (Health Ministry of Argentina, 2019)
Brazil	21	Aflatoxins	Cereal	Fumonisins in corn and corn products, AFM_1 in cheese and goat milk, DON, and ZEN in wheat products (100%)	Chromatography (MS, DAD, FLD)	Yes (Health Ministry of Brazil, 2021)
Chile	5	Aflatoxins and OTA	Capsicum	Aflatoxin, OTA, and DON in breakfast cereals, OTA in capsicum (100%)	Chromatography (FLD) and ELISA	Yes (Health Ministry of Chile, 1997)
Colombia	2	Aflatoxins	Corn arepas	AFM_1 in milk powder (100%)	Chromatography (FLD)	Yes (Health and Social Protection Ministry of Colombia, 2013)
Ecuador	4	Aflatoxins	Milk	AFM_1 in raw milk (100%)	Chromatography and ELISA	Only aflatoxins for raw milk (Ecuadorian Institute of Standardization, 2012)
Paraguay	4	Aflatoxins	Milk	AFM_1 in milk and milk formulas (100%)	ELISA	Only aflatoxins for yerba mate (National Institute of Technology, Standardization and Metrology of Paraguay, 2023)
Peru	3	*Fusarium* mycotoxins	Corn	Fumonisins in corn (100%)	Chromatography (MS)	No
Uruguay	6	*Fusarium* mycotoxins	Barley grain	Fumonisins in corn (97%)	Chromatography (FLD, DAD)	Yes (Republic of Uruguay, 1994)

et al. (2020) analyzed aflatoxins, fumonisins, ZEN, DON, T-2 toxin, HT-2, NIV, fusarone-x, 3-AcDON, 15-AcDON, Diacetoxyscirpenol, and OTA, finding 9% aflatoxins, 27% fumonisins, 15% ZEN, 13% DON and 3% OTA in breakfast cereals and 28% fumonisins (mean 196.2 ng/g), 7% ZEN (mean 47.5 ng/g), and 10% DON (mean 351.6 ng/g) in infant cereals. Another study found that 100% of the samples of breakfast cereals had fumonisins, and 10% had DON (Andrade et al., 2020). These authors also analyzed popcorn (n = 13) finding fumonisins in all samples, DON in 8% and ZEN in 15% of the samples; cornstarch and corn pasta (n = 7) finding fumonisins in all samples; corn grits-canjiquinha (n = 3), finding fumonisins in all samples, also DON and ZEN; and corn flour (n = 248) with an occurrence of 95.5% of fumonisins, 36% DON and 11% ZEN. The authors also analyzed wheat flour, pasta, crackles, and snacks, finding fumonisins, DON and ZEN in 0–97-2.5%, 13–100-66%, 0–100-100%, and 0–67-67%, respectively. The rice sampled was not contaminated (Andrade et al., 2020). Furthermore, Dos Santos et al. (2021) found DON in all wheat flour samples (n = 200), along with a 51% occurrence of ZEN and 13.5% of T-2 toxin. Iwase et al. (2023) found high occurrence and levels of DON (70%, mean 1,112 ng/g) in barley, also finding ZEN (40%, mean 256 ng/g). Also, in barley, dos Santos Caramês et al. (2022) found a 70% occurrence of enniatins. In cassava and tapioca, a low occurrence of aflatoxin was found in cassava flour (Ono et al., 2021). In oats samples, Pinheiro et al. (2021) found DON (44%), NIV (29%), 3-ADON (19%) and 15-ADON (8%). In beer, 80–100% of aflatoxins have been reported (Reboucas Rocha et al., 2023), and 21% of OTA was found in fermented coffee (Silva et al., 2023). In tilapia muscle, 19% of AFB_1 was found by Seraphin de Godoy et al. (2022). Finally, Abreu et al. (2023) analyzed 135 samples of cocoa beans by a multi mycotoxin analysis, finding AFB_1 (17%), AFB_2 (8%), AFG_1 (6%), AFG_2 (1%), AFBG (14%), OTA (20%), STG (8%), roquefortine C (1%), FB2 (6%), CIT (26%), mycophenolic acid (9%), paxilline (34%), ZEN (15%), cyclopiazonic acid (27%) and TeA (21%).

2.3 Chile

Five studies have been published regarding the occurrence of mycotoxins in foods for human consumption. Two studies focused on the presence of OTA and aflatoxins in capsicum, one of the most contaminated foods observed in a previous study (Foerster et al., 2020). The first study was part of the national monitoring program and found OTA in 59%–63% of the samples of capsicum (chili, paprika, merken, i.e., chili with spices), with levels of >LOQ-39.6 ng/g (Palma et al., 2023). The second study found OTA in all farmers' and markets' capsicum samples (n = 21) and 46%–75% occurrence of aflatoxin B_1 (Costa et al., 2022). A current study described the findings of OTA and aflatoxins of the mycotoxin monitoring program in all food samples; spices were the most contaminated, and aflatoxins were mainly found in nutmeg, pepper, and ginger, and their levels exceeded the limits of international regulations. For OTA, the occurrence was found in spices, coffee, cocoa, and flour (Calderon et al., 2023). The last two studies were in milk and milk formulas, where AFM_1 was found in 29% and 63%, respectively (Foerster et al., 2023), and in breakfast cereal, where DON, ZEN, fumonisins, OTA, and aflatoxins were found. Levels were below the Chilean regulatory limits but above the EU regulation for processed cereal-based foods and baby foods for infants and young children. Fumonisins were above 1,000 ng/g in three cornflake samples and DON >750 ng/g in one cornflake sample (Foerster et al., 2022).

2.4 Colombia

In the last years, only aflatoxins have been analyzed: in corn arepas (*n* = 168), 27% of AFB1 was found (Blanco-Lizarazo et al., 2019), and in milk powder (*n* = 51), AFM1 was found in 100% of the samples, and no positives for AFB1 were found (Marimón Sibaja et al., 2019).

2.5 Ecuador

Four studies were conducted in Ecuador, mainly on milk. Puga-Torres et al. (2020) found AFM1 in 100% of the 209 samples of raw milk and ZEN in 99.5% (Puga-Torres et al., 2021). Also, 78 breast milk samples were analyzed for aflatoxins, finding 13% of AFM1 and 9% of AFB_1 (Ortiz et al., 2018). Finally, 28 samples of corn were analyzed for aflatoxins, finding a 50% occurrence and levels of 0.42–107.7 μg/kg (Abel-Palacios et al., 2022).

2.6 Paraguay

Four studies have been reported in Paraguay, including wheat, beer, wine, milk, and milk formulas. The first described DON in wheat flour, bread, and crackers found high levels in most manufactured food (crackers, 0.038 ± 0.049 ng/g) (Arrua Alvarenga et al., 2019a). Furthermore, Arrua Alvarenga et al. (2019b) reported 25% OTA in wine and 24% of DON in beer. In milk formulas, AFM_1 was found in all fluid formulas analyzed (median 33.6 ng/kg) and in 9.75% of the powder formulas, but with greater levels (median 1820 ng/kg) (Arrua Alvarenga et al., 2021a). Finally, in UHT and pasteurized milk (sachet and cartons), Arrua Alvarenga et al. (2021b) found AFM_1 in 100% of the samples analyzed (*n* = 80).

2.7 Peru

Three studies were conducted in the period. The first study found aflatoxin with levels over 20 ng/g in 6/20 samples of capsicum, peanuts, and barley (Rojas Jaimes et al., 2021). Vásquez-Ocmín et al. (2023) found beauvericin in 59% of the 27 samples of quinoa, canihua, and kiwicha analyzed. Finally, Ducos et al. (2021) found fumonisins in 100% of the corn samples (*n* = 14) and DON (51%), NIV (6%), and ZEN (22%) in corn and wheat.

2.8 Uruguay

Six studies have data from 2018, five of them in grains and one of them in milk. The first publication found 67% of NIV in *n* = 154 barley (Garmendia et al., 2018), and the second found DON (90%) and ZEN (9%) also in barley (*n* = 89) (Palladino et al., 2021). The third study reported occurrences of fumonisins, DON, ZEN, and NIV in corn during 2018 and 2019, highlighting the high occurrences and levels of FB_1 (96.7%, mean 4,860 ng/g) and FB_2 (90.2%, mean 1,695 ng/g) in 2018 (del Palacio et al., 2023). The fourth publication found AFB_1 (8%) and fumonisins (4%) in sorghum grains (*n* = 50) (García y Santos et al., 2022). The fifth publication found 30% of AFs in 80 samples of wheat and sorghum grains (del Palacio and Pan, 2020). Finally, Capelli et al. (2019) found AFM_1 in 91.8% of cow milk samples from 18 farms in the country.

3 Discussion

Different mycotoxins produced by toxigenic fungi were detected in foods from all over South America. Most of the contaminated products have great economic importance in the region. The type of food and climate conditions of each country influenced the occurrence of mycotoxins (Figure 1A). Fungal contamination and mycotoxin occurrence in the food and feed chains represent a high risk to human and animal health and considerable economic losses due to restrictions to the domestic and international markets. Studies on the occurrence of mycotoxins in crops and processed food are essential because they are reliable approaches to evaluating the potential exposure risk of the populations to these contaminants (Chiotta et al., 2020).

Most of the mycotoxins analyzed in South America were the “traditional and regulated mycotoxins” like aflatoxins, AFM_1, OTA, fumonisins, DON, and ZEN, found with variable occurrences depending on the region, climatic conditions, and methodology used. Emerging and modified toxins like AOH, AME, TeA, TEN, ATX-I, and ALT have been studied only in Argentina and Brazil, where some studies have shown high occurrences. Also, in Brazil and Argentina, the methodology is more complex, using chromatography-mass spectrometry (LC-MS) with MS/MS detection, which can give more precise results. Robust analytical methods are crucial to ensuring food safety. LC-MS-based methods are becoming increasingly popular as they allow sensitive simultaneous determination of multiple fungal metabolites in many matrices (Gruber-Dorninger et al., 2017). ELISA methods are widely used in South America for being inexpensive and easy to use but tend to overestimate the levels because they usually detect other forms of mycotoxins (Gerding et al., 2015). Also, frequently, the limits of detection and quantification of these methods are higher than recommended. Despite these limitations, ELISA has proven to be an excellent qualitative method with high sensitivity, but additional quantification and validation must be made by chromatographic methods for reliable results (Gerding et al., 2015). In this regard, strengthening food safety laboratories and surveillance capabilities and establishing early warning systems is paramount. Also, countries must continue working and searching for efficient, cost-effective sampling and analytical methods to detect traditional and modified mycotoxins in the region.

Most studies in the region were conducted to find mycotoxins in grains and cereals, with an increasing analysis of AFM_1 in milk (Figure 1A). These studies were independent of the climatic and economic conditions of feed, so it was difficult to establish causality of the occurrences. In some countries like Argentina and Paraguay, feeding has been changed from grass to grains, which could increase

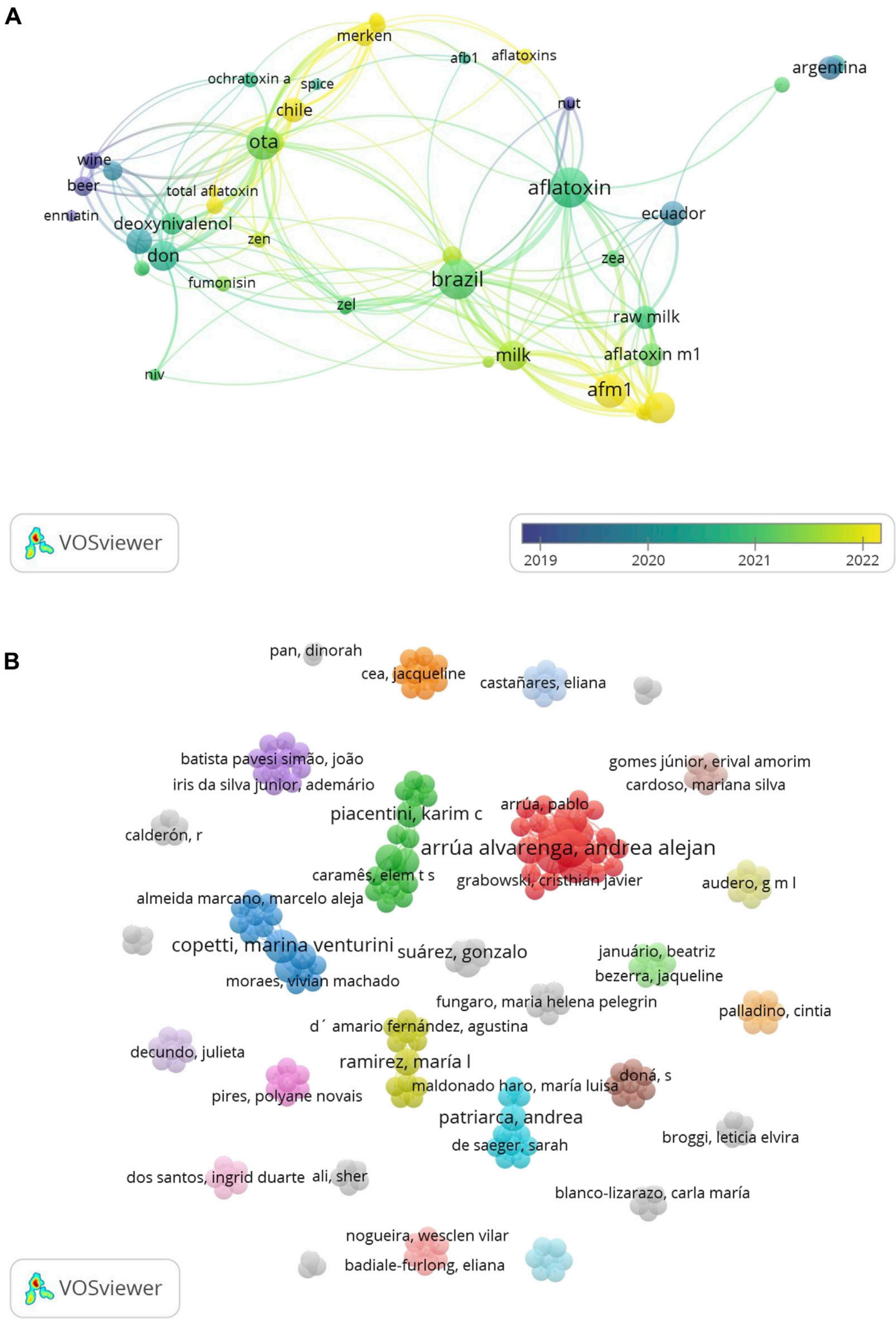

FIGURE 1
Scientific mapping of linked networks for different mycotoxins and foods in South America over the last 5 years. The methodology of the figure is described in the Supplementary Material. **(A)** Connections between the mycotoxin research in the countries of the study. **(B)** Collaboration map of the authors of the publications included in this mini review.

aflatoxin occurrence. In Brazil, milk production comes from different production systems, and frequently, there is no access to production control and history. This fact is a significant research gap in South America.

Furthermore, few countries have an estimation of exposure from the occurrences and levels of mycotoxins in food. Most of South America's current food safety regulations were based on international risk assessments like Codex Alimentarius (e.g., Chilean Food Sanitary Regulation, 2023) and the Southern Common Market, MERCOSUR (Organization of American States, 2022). This last regulation typically applies to food exports. Although harmonized regulatory limits would be beneficial from a commercial point of view, this does not necessarily promote equal protection of human health in a homogeneous way around the world. The risks associated with mycotoxins depend on both the hazard and the exposure. The danger posed by mycotoxins to humans is probably similar worldwide, but not the exposure, because of differences in the levels of contamination and diet habits; therefore, reliable exposure assessments for mycotoxins in each country are necessary (Food and Agriculture Organization, 2004). Some South American countries have an important gap in surveillance and internal regulatory issues, having no regulations or partial ones. For example, Paraguay only has an internal regulation for aflatoxins for yerba mate (National Institute of Technology, Standardization and Metrology of Paraguay, 2023) but lacks the rest of the foodstuffs. Only Brazil and Argentina have a special regulation for mycotoxins for foods destined for little children and infants (Health Ministry of Argentina, 2019; Health Ministry of Brazil, 2021). In this sense, it is crucial to continue working to bring awareness of mycotoxins as a public health issue.

Strategies to reduce mycotoxin contamination of foodstuffs require a multifaceted approach combining pre- and post-harvest interventions. In low- and middle-income countries in South America, where technology and infrastructure are not always adequate, ensuring low mycotoxin occurrence remains a significant challenge (Ducos et al., 2021). Furthermore, changes in climate systems suggest that slightly elevated CO_2 concentrations and interactions with temperature and water availability may stimulate the growth of some mycotoxigenic species, especially under water stress (Magan et al., 2011). For example, Paterson and Lima (2010) suggested that a significant risk of climate change will be developed in countries with temperate climates, like Chile and part of Argentina, which would be conducive to aflatoxin production, and that in colder climates, mycotoxins such as PAT and OTA may become more critical. The impact of climate change will also be remarkable for soil microbial populations; these will be affected and subsequently will affect the prevalence of some fungi. Due to the changes of given fungal species to colonize new environments, the profile of toxigenic species occurring in different geographical areas could be modified, leading to new mycotoxin risks in specific regions (Moretti et al., 2019). Given these potential impacts, it is crucial for research efforts to focus on monitoring the occurrence of mycotoxins in foods, evaluating population exposure, and understanding the prevalence of different toxigenic fungal species in various regions.

The following steps for South American countries are to increase food surveillance, internal mycotoxin regulation, biomonitoring analysis, and estimation of human health exposure based on contamination levels and dietary habits in each country. Epidemiological studies are urgently needed to understand the source of exposure in the population and the chronic health consequences of this exposure. Evidence on the intersection between climate change and health is limited in South America and has been generated in silos, with limited transdisciplinary research (Palmeiro-Silva et al., 2023). This information was corroborated in this study, where collaborations in research were null (Figure 1B). Effective connection and collaboration between disciplines and sectors in different countries is urgently needed to address this challenging research.

Author contributions

CF: Conceptualization, Formal Analysis, Methodology, Writing–original draft, Writing–review and editing. AM-S: Formal Analysis, Writing–original draft, Writing–review and editing. MVC: Formal Analysis, Writing–original draft, Writing–review and editing. AA: Formal Analysis, Writing–original draft, Writing–review and editing. LM: Formal Analysis, Writing–original draft, Writing–review and editing. MR: Formal Analysis, Writing–original draft, Writing–review and editing. AT: Supervision, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fchbi.2024.1400481/full#supplementary-material

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