Mycotoxin contamination in the Arab World: Highlighting the main knowledge gaps and the current legislation

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Abstract

Since the discovery of aflatoxins in the 1960s, knowledge in the mycotoxin research field has increased dramatically. Hundreds of review articles have been published summarizing many different aspects, including mycotoxin contamination per country or region. However, mycotoxin contamination in the Arab world, which includes 22 countries in Africa and Asia, has not yet been specifically reviewed. To this end, the contamination of mycotoxins in the Arab world was reviewed not only to profile the pervasiveness of the problem in this region but also to identify the main knowledge gaps imperiling the safety of food and feed in the future. To the best of our knowledge, 306 (non-)indexed publications in English, Arabic, or French were published from 1977 to 2021, focusing on the natural occurrence of mycotoxins in matrices of 14 different categories. Characteristic factors (e.g., detected mycotoxins, concentrations, and detection methods) were extracted, processed, and visualized. The main results are summarized as follows: i) research on mycotoxin contamination has increased over the years. However, the accumulated data on their occurrences are scarce to non-existent in some countries; ii) the state-of-the-art technologies on mycotoxin detection are not broadly implemented, neither are contemporary multi-mycotoxin detection strategies, thus showing a need for capacity-building initiatives; and iii) mycotoxin profiles differ among food and feed categories, as well as between human biofluids. Furthermore, the present work highlights contemporary legislation in the Arab countries and provides future perspectives to mitigate mycotoxins, enhance food and feed safety, and protect the consumer public. Concluding, research initiatives to boost mycotoxin research among Arab countries are strongly recommended.

Keywords: Arab countries, mycotoxins, food safety, research initiatives, regulations, mycotoxin biomarkers

Abbreviations

15-acetyl-deoxynivalenol (15-ADON), 3-acetyl-deoxynivalenol (3-ADON), Aflatoxin B1 (AFB1), Aflatoxin B2 (AFB2), Aflatoxin G1 (AFG1), Aflatoxin G2 (AFG2), Aflatoxin M1 (AFM1), Aflatoxins (AFs), Beauvericin (BEA), Citrinin (CIT), Deoxynivalenol (DON), Diacetoxyscirpenol (DAS), Enniatin-A (ENA), Enniatin-A1 (ENA-1), Enniatin-B (ENB), Enniatin-B1 (ENB-1), Enniatins (ENs), Enzyme-Linked Immunosorbent Assay (ELISA), European Union (EU), Fumonisin B1 (FB1), Fumonisin B2 (FB2), Fumonisin B3 (FB3), Fumonisins (FBs), Gas Chromatography-Electron Capture Detector (GC-ECD), Gas Chromatography-Flame Ionization Detector (GC-FID), Gas Chromatography-Tandem Mass Spectrometry (GC-MS/MS), High Performance Liquid Chromatography-Fluorescence Detector (HPLC-FLD), High Performance Liquid Chromatography-High Resolution Mass Spectrometry (HPLC-HRMS), High Performance Liquid Chromatography-Tandem Mass Spectrometry (HPLC-MS/MS), High Performance Liquid Chromatography-Ultraviolet Detector (HPLC-UV), Neosolaniol (NEO), Nivalenol (NIV), Ochratoxin A (OTA), Patulin (PAT), T-2 toxin (T-2), Thin layer Chromatography (TLC), Zearalenone (ZEN).

1. Introduction

Mycotoxins are known as toxic secondary metabolites produced by certain fungal species (Pitt and Miller 2017). The consequent negative impacts of mycotoxins on animal and human health, as well as agricultural and food industries, have put these natural contaminants at the forefront of myriad research areas, including mycology, plant pathology, food science, and toxicology (Wild and Gong 2009; Tola and Kebede 2016; Eskola et al. 2019). In general, toxigenic fungi can invade crops and other commodities in pre- and post-harvest stages under appropriate environmental conditions (Paterson and Lima 2010; Luo et al. 2018). For instance, *Fusarium* species often attack agronomic crops in the field, while *Aspergillus* and *Penicillium* species frequently grow on a wide array of food and feed matrices during storage (Perrone et al. 2020). Therefore, the risk of mycotoxin contamination remains extant throughout the entire food and feed production chain. The most notorious mycotoxins are aflatoxins (AFs); *Alternaria* toxins; citrinin (CIT); deoxynivalenol (DON); enniatins (ENs); ergot alkaloids; fumonisins (FBs); nivalenol (NIV); ochratoxin A (OTA); patulin (PAT); T-2 toxin (T-2); HT-2 toxin (HT-2); and zearalenone (ZEN) (Bhat et al. 2010; Ismaiel and Papenbrock 2015). These toxins are just a highlight, as scientists estimate the number of toxic fungal metabolites with the potential to contaminate food and feed over 400 chemical compounds (Bhat et al. 2010).

Numerous published review articles have almost exhaustively covered the mycotoxin research field, from the history of mycotoxins (Pitt and Miller 2017) to their synthesis (Ferrara et al. 2022), methods of detection (Alshannaq and Yu 2017; Jia et al. 2021), toxic effects on animals and humans (Bryden 2012; De Ruyck et al. 2015; Smith et al. 2016), methods for (pre- and post-harvest) control (Luo et al. 2018; Abdallah et al. 2019a; Haque et al. 2020), and risk assessment and characterization (Marin et al. 2013; Malir et al. 2023). Indeed, the natural occurrence or contamination of mycotoxins has been reviewed in several papers of various scopes. For example, some review papers focused on geographical delineations in Africa (Wagacha and Muthomi 2008; Darwish et al. 2014; Kebede et al. 2020), Asia (Streit et al. 2013; Shi et al. 2018; Sun et al. 2023), Europe (Streit et al. 2012; Luo et al. 2021), the United States (Wood 1992), and other regions of the world. Additionally, other reviews have delved into mycotoxin contamination per crop or food or feed and other categories such as cereals (Pereira et al. 2014; Pinotti et al. 2016; Leite et al. 2021), nuts (Kluczkovski 2019), dairy products (Becker-Algeri et al. 2016; Benkerroum 2016), fruits and vegetables (Nan et al. 2022), spices (Thanushree et al. 2019), feed (Binder et al. 2007; Streit et al. 2012; Gruber-Dorninger et al. 2019; Pietsch 2020; Tolosa et al. 2021), and (human) biofluids (Warth et al. 2016; Escrivá et al. 2017; Al-Jaal et al. 2019; Arce-López et al. 2020). However, mycotoxin contamination in the Arab world, which includes 22 countries in Africa and Asia, has not yet been specifically reviewed. Unlike preceding reviews focusing on a particular country or continent, this review aims to comprehensively investigate mycotoxin contamination across all Arab League countries. Furthermore, the present work highlights the existing legislation in the Arab countries and provides future perspectives for mitigating mycotoxins, enhancing food and feed safety, and protecting consumers. Within these perspectives, some research initiatives are suggested to bolster mycotoxin research in Arab countries.

2. Description of workflow: Data collection, refinement, processing, and visualization

Searching the online literature covered all indexed publications at major stream databases (e.g., Web of Science, Scopus, PubMed, and Google Scholar) and non-indexed papers from other scientific journals and publishers. Only publications that focused on the natural occurrence of any mycotoxin(s) were considered. Besides, scientific articles or publications written in Arabic (the official language of all Arab countries) or French (a spoken language in some countries like Algeria, Tunisia, and Morocco) were included in the current work. At least one of the following keywords—mycotoxins, mycotoxin, aflatoxins, aflatoxin B1, aflatoxin B2, aflatoxin G1, aflatoxin G2, aflatoxin M1, ochratoxins, ochratoxin A, fumonisins, fumonisin B1, zearalenone, emerging mycotoxins, masked mycotoxins, modified mycotoxins, enniatins, deoxynivalenol, and patulin— was utilized with each country name of the 22 Arab countries (Algeria, Bahrain, Comoros, Djibouti, Egypt, Iraq, Jordan, Kuwait, Lebanon, Libya, Mauritania, Morocco, Oman, Palestine, Qatar, Saudi Arabia, Somalia, Sudan, Syria, Tunisia, United Arab Emirates, and Yemen) during the search. Additionally, other keywords such as occurrence, incidence, survey, detection, contamination, quantitation, quantification, analysis, cereals, grains, maize, corn, wheat, barley, rice, nuts, peanuts, milk, dairy products, egg, juice, drinks, coffee, wine, fruits, dried fruits, oils, spices, food, baby food, breakfast cereals, animal feed, meat, chicken, blood, urine, plasma, human biofluids, and breast milk were combined with at least one of the previously listed keywords for each country used in the study. The matrices were grouped into 14 categories (**Table 1**) based on the origin (cereals, nuts, fruits, etc) or their source (animal feed, human biofluids, oils, etc) to facilitate data analysis. Some papers were excluded for lacking sufficient details or being presented in a way that hindered the extraction of the relevant information needed for this work.

Data processing and visualization were conducted using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA), R 4.0.2 (R Foundation for Statistical Computing, Vienna, Austria) with ggplot2, GraphPad Prism 10.1.0 (GraphPad Software, Boston, Massachusetts USA), and online tools such as RAWGraphs 2.0 beta. Qualitative data, including the type of matrix, targeted mycotoxins, detected mycotoxins, analytical techniques, year of publication, and method development; as well as quantitative data such as the number of collected samples, number of contaminated samples, and mycotoxin concentrations (mean, median, minimum, and maximum levels in µg/kg), were all potential variables listed for each country.

Table 1: Categories of different agriculture crops, food, feed, and other matrices included in this review

Category	Matrices
Animal feed	Alfalfa hay, commercial animal feed, barley used in feed, broiler starter, broilers mixed feed, calf fattening mixed feed, egg production mixed feed, fish feed, maize, milk production mixed feed, mixed feed, poultry feed, silage, soybean animal meal, wheat used in feed
Animal meat product (edible)	Chicken, egg, fish, liver, luncheon meat, meat, meat basterma, sausage
Baby food	Cereal-based baby foods, corn-based infant food, infant formula
Biomarkers (human)	Blood, breast milk, plasma, serum, urine
Cereals	Barley, bsissa, burghul, corn, couscous, flour, millet, oat, rice, rice germ, rye, sorghum, soup (cereal), triticale, wheat, white maize, yellow maize
Cereal products	Biscuits, bread, cereal breakfast, corn flakes, pasta, popcorn
Dairy products	Buffalo's milk, butter, camel milk, cow milk, goat milk, ice cream, koshk, labna (or labneh), powdered milk, raw milk, cheeses (all types), sheep milk, ultra-high-temperature milk, yogurt
Juices and drinks	Beer, coffee, grape juice, green tea, juice, must, wine
Legume and pulses	Beans, groundnuts, lentil, moong, peanut butter, peanuts, peas, soybean
Nuts	Almonds, Brazil nuts, cashew nuts, hazelnuts, macadamias, pecans, pine, nuts, pistachios, walnuts
Oils	Groundnut oil, sunflower oil, vegetable oil, other edible oil
*Other	Coconut, compote, honey, noodles, other food, pickled olives, sunflower seeds, tobacco
Spices and herbs	Pepper, clove powder, coriander, cumin, fenugreek, ginger, laurel, red paprika, rosemary, verbena
Vegetables and fruits (including dried)	Dates, dried dates, dried figs, dried raisins, fresh apples, grapes, jam

* The category "other" comprises matrices that could not be grouped into any other defined categories

3. General overview of mycotoxin occurrence in the Arab world

To our knowledge, data on the natural occurrence of mycotoxins in food, feed, or human biofluids are available from all Arab countries, except Djibouti and Mauritania (**Figure 1**). The first paper reporting mycotoxin occurrence in the Arab countries was published in 1977, detailing the presence of AFB1 and AFB2 in beans, maize, wheat, and peanut samples collected from three major Egyptian cities (Girgis et al. 1977). Since then and until the conclusion of 2021, our literature search has identified 306 articles, including one in Arabic and three in French, focusing on the natural occurrence of mycotoxins. Papers reporting the production of mycotoxins from isolated fungi under controlled laboratory conditions were excluded. Egypt had the highest number of publications (n = 95), followed by Tunisia (n = 49), Saudi Arabia (n = 31), and Morocco (n = 24) as the top contributors. Some papers encompassed multiple survey studies across several Arab countries, resulting in a total of 312 survey studies within 306 articles. The complete list of publications per country used in the current work is available in the supplementary data (**List S1**).

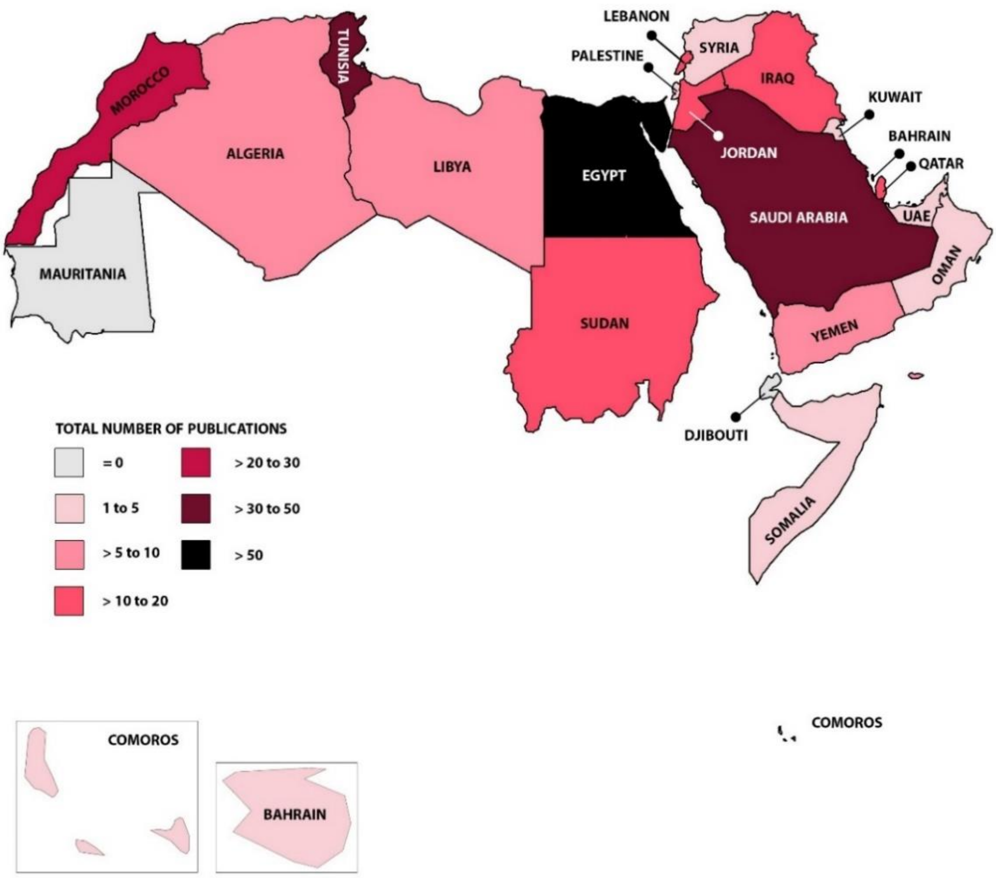

Figure 1: Choropleth map illustrating the number of published articles concerning the natural occurrence of mycotoxins in food, feed, human biofluid, and other samples from the Arab world from 1977 to 2021.

The number of publications on the natural occurrence of mycotoxins per year is depicted in **Figure 2**. Overall, there was an upward trend in the published papers each year, reflecting the growing emphasis on mycotoxin research and food and feed safety in the Arab League countries. From 1977 to 2000, Egypt contributed to approximately 66% of the published data on mycotoxins (31 papers out of 47). Notably, between 1978 and 1984, no reports on mycotoxin occurrences were documented, creating a discontinuity in the records. After 2000, three countries (Tunisia, Saudi Arabia, and Morocco) and Egypt became primary contributors to the available data. Supplemental **Figure S1** is an alluvial diagram showing the number of publications on mycotoxin occurrence per country and year. Interestingly, the number of publications for 2019, 2020, and 2021 is nearly five times more than those from 2000, 2001, and 2002 (**Figure 2**), indicating an increased interest in mycotoxin monitoring in different matrices over the years.

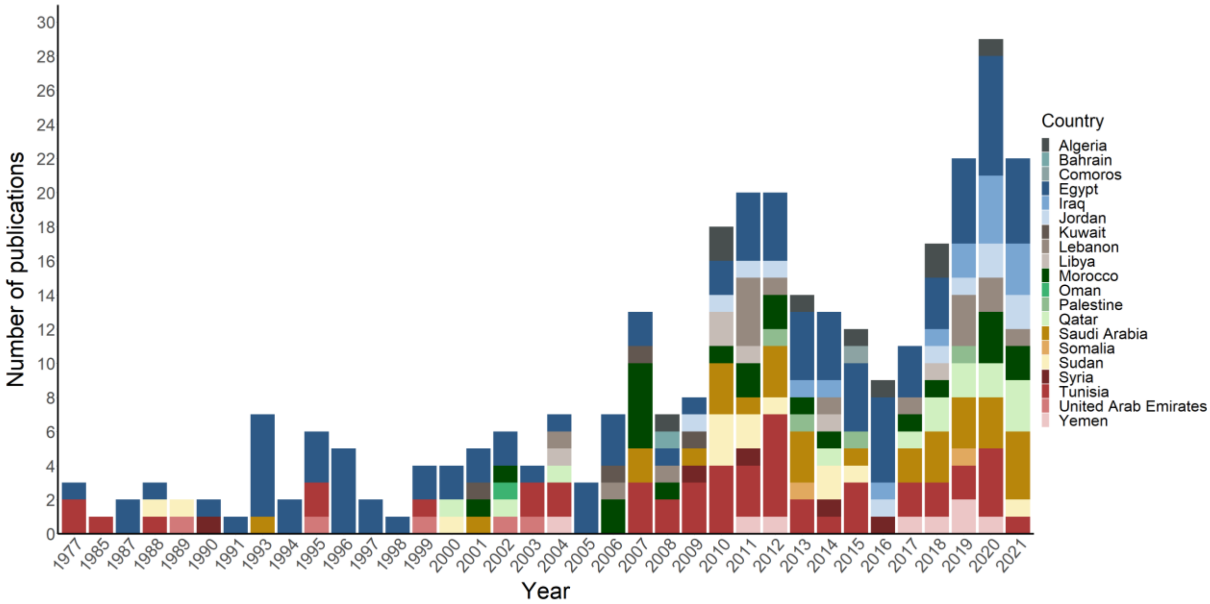

Figure 2: Annual number of publications on the natural mycotoxin occurrence in food, feed, human biofluid, and other samples from the Arab world from 1977 to 2021.

4. Detection and quantification of mycotoxins in food, feed, human biofluids, and other categories from Arab countries

The detection and quantitation of mycotoxins have been effectively achieved in almost all kinds of foods, many animal feeds, and several human biofluids and tissues through diverse analytical techniques (Bhat et al. 2010; Arce-López et al. 2020; Jia et al. 2021). Semi-quantitative chromatographic techniques, such as thin layer chromatography (TLC), were widely employed for mycotoxin detection, and they are still commonly used techniques in many developing countries (see below in this section). Gas chromatography-electron capture detector (GC-ECD), gas chromatography-flame ionization detector (GC-FID), and gas chromatography-tandem mass spectrometry (GC-MS/MS) were successfully applied for mycotoxin analysis. However, a derivatization step was necessary for mycotoxin quantification. This complication has steered the focus toward more practical techniques that facilitate sensitive multi-mycotoxin detection using liquid chromatography-based instruments, including high performance liquid chromatography-ultraviolet detector (HPLC-UV), high performance liquid chromatography-fluorescence detector (HPLC-FLD), high performance liquid chromatography-tandem mass spectrometry (HPLC-MS/MS), and high performance liquid chromatography-high resolution mass spectrometry (HPLC-HRMS). Recently, the prevalent trend in mycotoxin quantification is the implementation of multi-mycotoxin detection methods in a single run using HPLC-MS/MS due to its (ultra-)high level of selectivity and sensitivity (Malachová et al. 2014). Immunological-based methods, such as enzyme-linked immunosorbent assay (ELISA), offer a practical approach for rapidly screening and quantifying various major mycotoxins in diverse food and feed matrices.

In the Arab world, all these analytical techniques were applied, at varying degrees, to detect and quantify mycotoxin(s) in various matrices such as food, feed, (human) biological fluids, and others. **Figure 3** depicts the analytical techniques used in each Arab country from 1977 to 2021. The following techniques were predominantly used for the (quantitative) analysis of mycotoxin: HPLC-FLD (133 articles), ELISA (65 articles), TLC (49 articles), HPLC-MS/MS (44 articles), and HPLC-UV (26 articles). It was also observed that some publications used more than one analytical to detect different mycotoxins within the (same) matrix of interest. Notably, HPLC-FLD was the main technique used for (multiple) mycotoxins in Egypt (after TLC), Tunisia, Saudi Arabia, Morocco, Lebanon, Algeria, Qatar, and Sudan (**Figure 3**). Most of these papers employing HPLC-FLD focused on the detection and quantification of AFB1, individual members of AFs (AFB1, AFB2, AFG1, and AFG2), or total AFs after pre- or post-column derivatization. In addition, quantitation of aflatoxin M1 (AFM1) was also conducted in various dairy products, alongside the determination of AFB1 adduct in human biofluids. AFs were detected in animal feeds and animal feed ingredients from Egypt (Rodrigues et al. 2011; Mohamed et al. 2017; Abdallah et al. 2019b), Jordan, Kuwait, Morocco, Saudi Arabia, Sudan, Syria, and Yemen (Beg et al. 2006; Zinedine et al. 2007b; Rodrigues et al. 2011; Abudabos et al. 2017). Moreover, AFs were found in edible animal products and fish from Egypt (Mohamed et al. 2017; Hamad et al. 2021), several types of meat collected from Saudi Arabia (Elzupir and Abdulkhair 2020), and egg and meat samples from Jordan using HPLC-FLD (Herzallah 2009). Cereals and cereal products from Algeria (Riba et al. 2010), Egypt (Madbouly et al. 2012; Deabes et al. 2018; Hathout et al. 2020), Jordan (Omar et al. 2020), Lebanon (Joubrane et al. 2011, 2020), Morocco (Zinedine et al. 2007b), Palestine (Ahmed et al. 2015), Qatar (Abdulkadar et al. 2002, 2004), Saudi Arabia (Elzupir et al. 2018; El Tawila et al. 2020), Sudan (Elbashir and Ali 2014), and Tunisia (Ghali et al. 2009, 2010; Jedidi et al. 2017) were documented to be contaminated with AFs.

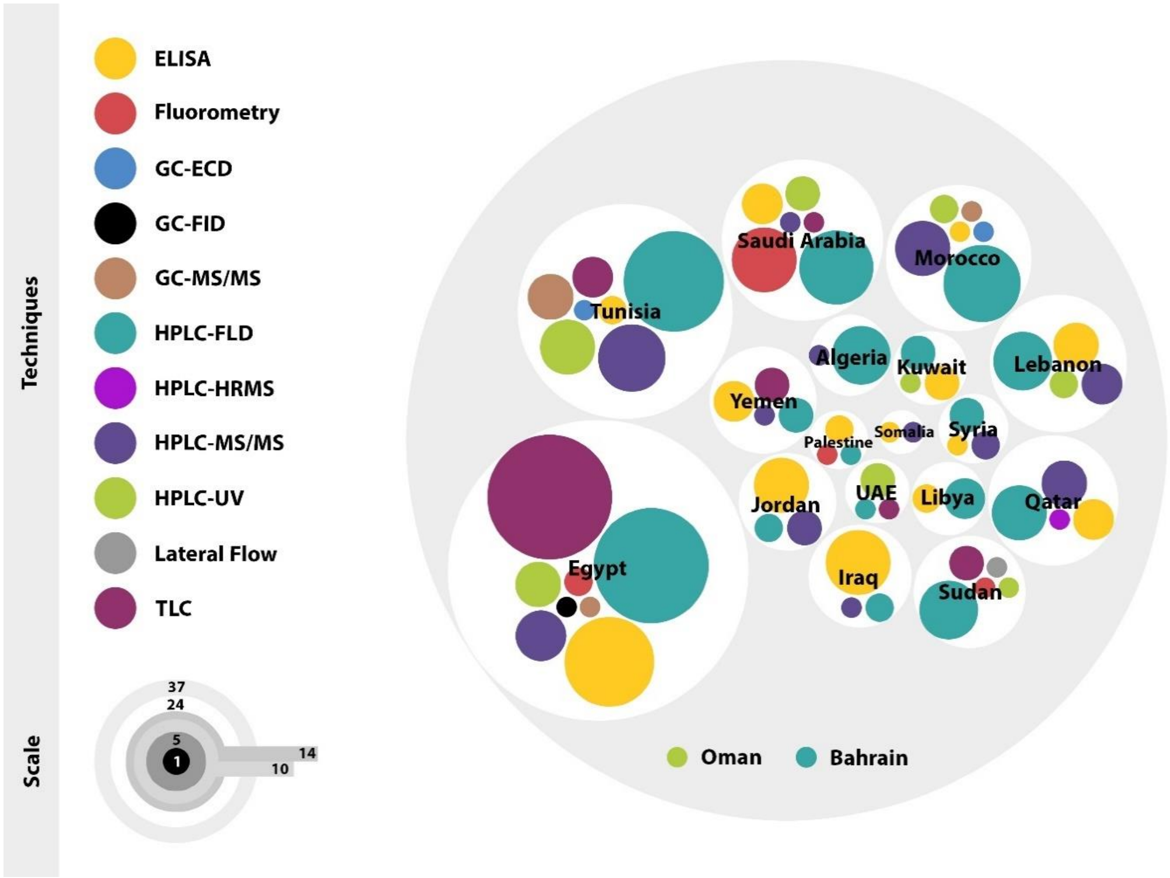

Figure 3: Analytical techniques utilized for screening and quantifying mycotoxins in different samples (food, feed, human biofluids, and others) across all Arab countries from 1977 to 2021. These techniques include: ELISA, Enzyme-Linked Immunosorbent Assay; GC-ECD, Gas Chromatography-Electron Capture Detector; GC-FID, Gas Chromatography-Flame Ionization Detector; GC-MS/MS, Gas Chromatography-Tandem Mass Spectrometry; HPLC-FLD, High Performance Liquid Chromatography-Fluorescence Detector; HPLC-HRMS, High Performance Liquid Chromatography-High Resolution Mass Spectrometry; HPLC-MS/MS, High Performance Liquid Chromatography-Tandem Mass Spectrometry; HPLC-UV, High Performance Liquid Chromatography-Ultraviolet Detector; TLC, Thin layer Chromatography.

AFs were detected in peanuts or processed peanut butter samples from Algeria (Guezlane-Tebibel et al. 2013; Ait Mimoune et al. 2018), Egypt (Abdel-Rahman et al. 2019), Morocco (Juan et al. 2008b), Sudan (Elshafie et al. 2011; Elzupir et al. 2011), and Syria (Haydar et al. 1990). In nuts, quantification of AFs was conducted in several popular types across Algeria (Fernane et al. 2010; Ait Mimoune et al. 2018), Bahrain (Musaiger et al. 2008), Morocco (Juan et al. 2008b), Qatar (Abdulkadar et al. 2000, 2002, 2004), Saudi Arabia (El tawila et al. 2013; Abdullah AlFaris et al. 2020), and Tunisia (Ghali et al. 2009). Additionally, AFs/AFB1 were detected in dried figs from Algeria (Ait Mimoune et al. 2018), Jordan (Omar et al. 2020), Morocco (Juan et al. 2008b), Qatar (Abdulkadar et al. 2004), and Syria (Haydar et al. 1990). For juices and drinks, AFs were found in coffee beans from Jordan (Omar et al. 2020), Qatar (Al-Ghouti et al. 2022), and Saudi Arabia (Bokhari 2007a; El Tawila et al. 2020), and in must from Lebanon (El Khoury et al. 2008). Researchers detected AFs in different types of oil from Sudan (groundnut, sunflower, and vegetable oil) (Elzupir et al. 2010; Idris et al. 2010; Mariod and Idris

2015), as well as AFs/AFB1 in different spices from Algeria (Azzoune et al. 2016), Bahrain (Musaiger et al. 2008), Morocco (Zinedine et al. 2006), and Qatar (Abdulkadar et al. 2004; Hammami et al. 2014).

Dairy products were assessed for AFM1 contamination in various studies (Haydar et al. 1990; El-Sayed Abd Alla et al. 2000; Elgerbi et al. 2004; Zinedine et al. 2007a; Redouane-Salah et al. 2015; Hassan et al. 2018; Abdallah et al. 2019b; Daou et al. 2020; Mannani et al. 2021). In addition, meat products, milk, and eggs from Jordan were investigated for AFs levels, including AFM1 (Herzallah 2009). Over the last 20 years in Egypt, AFM1 contamination was studied using HPLC-FLD in human biofluids such as serum (Mokhles et al. 2007; Raafat et al. 2021), urine (Polychronaki et al. 2008; Piekkola et al. 2012; Saad-Hussein et al. 2013), and breast milk (El-Sayed Abd Alla et al. 2000; El-Sayed et al. 2002; Hassan et al. 2006a; Polychronaki et al. 2006). Similar studies used HPLC-FLD to quantify AFM1 in human serum samples collected from Iraq (Suhail et al. 2020) and Saudi Arabia (Farag et al. 2018), breast milk from Sudan (Elzupir et al. 2012), and umbilical cord blood samples from the United Arab Emirates (Abdulrazzaq et al. 2002). OTA was frequently detected using HPLC-FLD in numerous types of coffee from Egypt (H.M. Alkhalifah et al. 2013), Qatar (Abdulkadar et al. 2004), and Saudi Arabia (Bokhari 2007a; H.M. Alkhalifah et al. 2013). Similarly, OTA was also found in soft drinks such as beer, must, wines, and others from Lebanon, Morocco, and Tunisia (Filali et al. 2001; Assaf et al. 2004; El Khoury et al. 2006; Melki Ben Fredj et al. 2007; Lasram et al. 2013). Moreover, OTA was detected using HPLC-FLD in grapes, dried figs, and dried raisins from Tunisia, Morocco, and Qatar (Maaroufi et al. 1995; Abdulkadar et al. 2004; Lasram et al. 2007, 2012; Zinedine et al. 2007c), spices and herbs from Qatar and Tunisia (Abdulkadar et al. 2004; Zaied et al. 2010), different types of nuts from Algeria, Morocco, Qatar, and Tunisia (Abdulkadar et al. 2004; Zinedine et al. 2007c; Zaied et al. 2010; Fernane et al. 2010), and peanuts from Morocco and Tunisia (Zinedine et al. 2007c; Zaied et al. 2010). Furthermore, OTA detection was documented in human serum or plasma (Maaroufi et al. 1995; Wafa et al. 1998; El-Sayed et al. 2002; Hassen et al. 2004a; Hassan et al. 2006b), breast milk (El-Sayed Abd Alla et al. 2000), and urine (Wafa et al. 1998; Hassen et al. 2004b) mainly from Egypt and Tunisia, with a few studies from Lebanon, Libya, and Morocco. Cereals, cereal-based products, animal feeds, and animal products were investigated using HPLC-FLD for the presence of OTA (Abdulkadar et al. 2004; Assaf et al. 2004; Beg et al. 2006; Zinedine et al. 2006, 2007c; Zaied et al. 2009; Rodrigues et al. 2011; Hamad et al. 2021; Algammal et al. 2021). Moreover, the (co-)occurrences of other toxins, particularly in animal feed and cereals, including FBs (Zinedine et al. 2006; Fatah et al. 2015), DON (Bensassi et al. 2010, 2011), NIV (Al-Julaifi and Al-Falih 2001), CIT (Zaied et al. 2012a), T-2 and HT-2 (Al-Julaifi and Al-Falih 2001), and ZEN (Abdulkadar et al. 2004; Musaiger et al. 2008; Rodrigues et al. 2011; Zaied et al. 2012b; Abdallah et al. 2019b) were also detected.

ELISA was mainly used to detect AFM1 in dairy products in Egypt (Salem 2002; Motawee et al. 2009; Amer and Ibrahim 2010; Aiad 2013), but also in some sporadic surveys conducted in Lebanon (El Khoury et al. 2011; Assem et al. 2011; Elkak et al. 2012), Qatar (Hassan et al. 2018), Syria (Ghanem and Orfi 2009), Palestine (Al Zuheir and Omar 2012), Kuwait (Dashti et al. 2009), Saudi Arabia (Waqar Ashraf 2012), Jordan (Omar 2012), Libya (Gunbeaj et al. 2018), Iraq (Najim 2014), and Tunisia (Abbès et al. 2012). Furthermore, AFM1 quantitation was performed in breast milk samples from Egypt (Tomerak et al. 2011; El-Tras et al. 2011), Morocco (Cherkani-Hassani et al. 2020a), Jordan (Omar 2012), Lebanon (Elaridi et al. 2017), and Kuwait (Dashti et al. 2009). ELISA was also employed to survey OTA in breast milk from Morocco (Cherkani-Hassani et al. 2020b). Other matrices, such as cereals and commercial animal feed matrices, were also collected to analyze different mycotoxins using ELISA. For instance, Ghali *et al.* conducted analyses for AFs, AFB1, OTA, and ZEN in rice, barley, wheat, and sorghum samples from nine areas in Tunisia (Ghali et al. 2008), while one study from Somalia used ELISA for the analysis AFs, DON, and FBs in maize samples (Probst et al. 2014). For animal feed, four mycotoxins (AFs, T2, DON, ZEN, and FBs) were screened for their contamination in different types of feed from Jordan (Bani Ismail et al. 2020), while other studies from Egypt, Iraq, Kuwait, and Tunisia focused mainly on AFs detection. Additionally, nuts from Iraq and Saudi Arabia were analyzed for the contamination of AFs (Waqar Ashraf 2012; Abdulla 2013).

TLC was predominantly used to detect AFs in various matrices, including human plasma and urine, from Egypt. However, a few studies from Saudi Arabia, Sudan, the United Arab Emirates, Tunisia, and Yemen documented the detection of AFs using this technique. Other toxins like OTA and CIT were detected by TLC in cereals from Egypt (El-Sayed 1996) and Tunisia (Hadidane et al. 1985; Bacha et al. 1988), alongside DAS and T-2 in cereal grains, collected from the Delta region and Upper part of Egypt (Abdel-Hafez et al. 1987; El-Maghraby et al. 1995). Despite being considered an old-fashioned technique, recent papers utilized TLC to detect AFM1 in dairy products from Egypt (Ismaiel et al. 2020) and three toxins (ZEN, T-2, and FBs) in cereals from Yemen (Al-Jobory et al. 2017).

HPLC-MS/MS had more implementation in Tunisia, Morocco, and Egypt (**Figure 3**). Until 2021, there are 12 papers from Tunisia using HPLC-MS/MS. Among these, six studies combined HPLC-MS/MS with GC-MS/MS to quantify 20 to 24 mycotoxins in infant food, cereals, cereal-based foods, commercial animal feed, and silage (Juan et al. 2017, 2019, 2020; Oueslati et al. 2018, 2020; Bouafifssa et al. 2018). Other studies in Tunisia used HPLC-MS/MS for two or multiple mycotoxins in human urine (Belhassen et al. 2015), cereals and cereal-based products (Oueslati et al. 2012, 2014), different types of spices and herbs (Gambacorta et al. 2019; Potortì et al. 2020), and dried fruits (Azaiez et al. 2015). For Morocco, (multi-)mycotoxins HPLC-MS/MS-based analysis was performed in seven studies covering cereals and cereal-based products (Zinedine et al. 2011, 2017; Sifou et al. 2011; Mahnine et al. 2012;

Blesa et al. 2014), infant food (Mahnine et al. 2012), and green tea (El Jai et al. 2021). In addition, HPLC-MS/MS with GC-MS/MS were utilized to detect 20 mycotoxins in pasta samples marketed in Morocco (Bouafifssa et al. 2018). In Egypt, Abdallah *et al.* conducted a quantitative HPLC-MS/MS analysis of more than 259 mycotoxins and other microbial metabolites in maize, animal feeds, sugarcane grass, sugarcane juice, and dried dates samples (Abdallah et al. 2016, 2017, 2018b), while Piekkola *et al.* and Motawee *et al.* used HPLC-MS/MS to detect DON and its metabolites (deepoxy-deoxynivalenol) in urine samples and AFM1 in raw dairy milk, respectively (Motawee et al. 2004; Piekkola et al. 2012). Single mycotoxin detection like PAT detection in apple, apple juice, and apple-based infant food samples was conducted in Qatar (Hammami et al. 2017), while other researchers analyzed 19 to 20 mycotoxins in human serum samples (Al-Jaal et al. 2020, 2021), eight mycotoxins in nuts and spices (Al Jabir et al. 2019), and 11 mycotoxins in baby food (Ul Hassan et al. 2018). Other countries such as Lebanon, Jordan, Algeria, Yemen, Saudi Arabia, Iraq, Syria, and Somalia had fewer studies (**Figure 3**).

HPLC-UV analysis was conducted to detect AFB1 or AFs in different matrices (spices, medical plants, nuts, dried vegetables, cereals, animal feed, and human biofluids) from Egypt (see **Supplementary data**) and AFM1 in breast milk samples from the United Arab Emirates (Saad et al. 1995; Abdulrazzaq et al. 2003). Deabes *et al.* used HPLC-UV to confirm the contamination of cyclopiazonic acid in different Egyptian maize samples (Deabes et al. 2018), while Rodrigues *et al.* detected B-trichothecenes (NIV, DON, and acetylated forms of DON) in animal feeds/feed ingredients from different countries including Egypt, Jordan, Sudan, Syria, and Lebanon (Rodrigues et al. 2011). DON was detected using HPLC-UV from Tunisian barley and durum wheat (Bensassi et al. 2010, 2011). PAT was quantified in different Tunisian apple juice, apple-based jam, and apple-based baby food samples (Mhadhbi et al. 2007; Zaied et al. 2013; Zouaoui et al. 2015), as well as in apple juice from Saudi Arabia (Gashlan 2008; Al-Hazmi 2010). Finally, enniatins ENs (ENA, ENA-1, ENB, and ENB-1), beauvericin (BEA), and fusaproliferin (FUS) were detected in cereals and cereal products from Tunisia (Oueslati et al. 2011) and Morocco (Zinedine et al. 2011).

Fluorometry was used in 14 articles to screen different mycotoxins, mainly AFs. For example, total AFs and OTA in animal meat products from Egypt (Abd-Elghany and Sallam 2015), AFM1 in animal dairy products from Sudan (Ali et al. 2014), AFs, ZEN, and OTA in animal feed samples from Saudi Arabia (Bokhari 2010), AFs and OTA in spices and herbs from Saudi Arabia (Gherbawy and Shebany 2018), AFs and sterigmatocystin (STE) in spices from Saudi Arabia (Bokhari 2007b), AFs in different nut samples from Saudi Arabia (El tawila et al. 2013), AFs in honey samples from Palestine (Swaileh and Abdulkhaliq 2013), and CIT in paddy rice from Egypt (Abd-Allah and Ezzat 2005).

GC-MS/MS (7 articles) was used to quantify multiple mycotoxins in different matrices such as type A and B trichothecenes in chicken liver samples from Egypt (Mahmoud et al. 2018), several mycotoxins in barley and barley-derived products from Tunisia (Juan et al. 2017), nine mycotoxins (DON, 3-ADON, 15-ADON, NIV, NEO, DAS, T-2, HT-2, and ZEN) in cereals and cereal-based products intended for infant consumption in Tunisia (Oueslati et al. 2018, 2020), seven mycotoxins (NIV, HT-2, T-2, DON, 3-ADON, 15-ADON, and FUS) in pasta samples from Morocco (Bouafifssa et al. 2018), and eight mycotoxins (NIV, DON, 3-ADON, 15- ADON, DAS, NEO, T-2, and HT-2) in silage samples and commercial animal feed samples from Tunisia (Juan et al. 2019, 2020). On the other hand, an in-house HPLC-HRMS validated method was used to detect 14 mycotoxin biomarkers, including four AFs (AFB1, AFB2, AFG2, and AFM1), CIT, cyclopiazonic acid, FB1, OTA, ochratoxin B, roquefortine C (ROC), STE, T-2, β-zearalenol (β-ZEL), and α-zearalenol (α-ZEL) in 559 urine samples of adult Qatari population (Al-Jaal et al. 2021). Conversely, Abdalmahmoud *et al.* utilized the lateral flow technique, using a commercial kit to screen for the presence of AFM1 in raw cow milk samples (n = 80) marketed at Gedarif town in Sudan (Abdalmahmoud et al. 2021).

The implementation of single or multiple mycotoxin detection strategies in the conducted survey studies across Arab countries from 1977 to 2021 is illustrated in **Figure 4**. The term "targeted mycotoxins" refers to the application of single or (simultaneous) multi-mycotoxin detection strategies, while the "detected mycotoxins" indicates the reported (co-)occurrence of mycotoxins per study. Many of these surveys covered multiple mycotoxins by adopting a "one mycotoxin detection per matrix" strategy (i.e., diverse food and feed matrices were investigated, each targeting a distinct mycotoxin). In another case, different mycotoxins were sometimes targeted within the same matrix, but separate extraction or analytical methods were performed for each mycotoxin or group of metabolites. Thus, these two approaches did not implement a "simultaneous" multi-mycotoxin detection strategy. For instance, Zinedine *et al.* analyzed maize for FB1, OTA and ZEN contamination, wheat and barley for OTA, and different spices for AFs (Zinedine et al. 2006). The individual analysis of AFB1, AFB2, AFG1, AFG2, CIT, DON, OTA, and ZEN was performed in different food categories collected from different locations in Egypt (Abdelhamid 1990). Additionally, Rodrigues *et al.* targeted 15 mycotoxins (AFB1, AFB2, AFG1, AFG2, DAS, DON, acetylated DON, FB1, FB2, FB3, NIV, T-2, HT-2, and ZEN) in 324 samples of different grains and animal feed collected from Algeria, Egypt, Jordan, Lebanon, Sudan, Syria, the United Arab Emirates, and Yemen, as well as other non-Arab countries. These mycotoxins were extracted and analyzed using different extraction methods and analytical instruments (Rodrigues et al. 2011). Another example is Ul Hassan *et al.* who analyzed multiple mycotoxins (AFB1, AFB2, AFG1, AFG2, OTA, ZEN, T-2, HT-2, FB1, FB2, and DON) in cereal-based baby food using different extraction methods (Ul Hassan et al. 2018). Also, Jedidi *et al.* used different techniques to detected various mycotoxins, such as HPLC-FLD for FB1, FB2, and ZEN; HPLC-UV for T-2, and HT-2 ; and GC–ECD for DON and NIV (Jedidi et al. 2021).

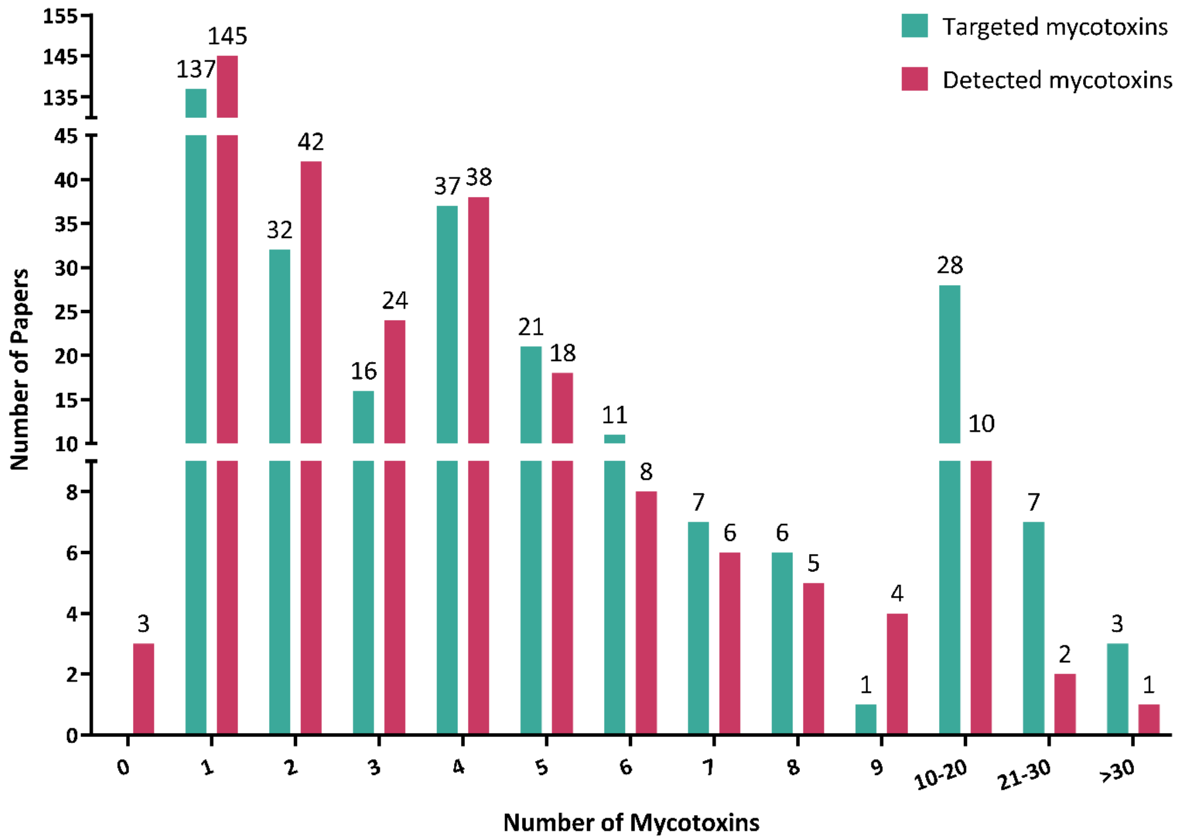

Figure 4: Number of papers that implemented single or (simultaneous) multi-mycotoxin detection strategies through counting targeted (blue) and detected (red) mycotoxins in the conducted survey studies across Arab countries from 1977 to 2021. The term "targeted mycotoxins" refers to the implementation of single or (simultaneous) multi-mycotoxin detection strategies, while "detected mycotoxins" refers to the (co-)occurrence of mycotoxins.

For the single mycotoxin detection strategy, approximately 45% (*n* = 138) of the publications focused on a sole mycotoxin (**Figure 4**), mainly AFM1, OTA, AFB1, and AFs (total AFs were considered as one metabolite in this work). Besides, a few papers targeted PAT, CIT, STE, DON, FB1, or ZEN. On the other hand, around 9% (*n* = 29) of the total publications targeted between 10 to 20 different mycotoxins, while only 2% (*n* = 7) targeted from 21 to 30 mycotoxins (**Figure 4**). Notably, merely three publications detected more than 30 targeted analytes in maize and animal feed (Abdallah et al. 2017), sugarcane juice (Abdallah et al. 2016), and palm dates (Abdallah et al. 2018b). Other authors implemented (simultaneous) multi-mycotoxin detection methods to target several mycotoxins in various type of matrices from Algeria (15 mycotoxins) (Mahdjoubi et al. 2020), Lebanon (12 mycotoxins) (El Darra et al. 2019), Morocco (18 mycotoxins) (Blesa et al. 2014), Qatar (19 mycotoxins) (Al-Jaal et al. 2021), Syria (25 mycotoxins) (Alkadri et al. 2014), and Tunisia (22 mycotoxins) (Oueslati et al. 2014).

Interestingly, most, if not all, of the survey studies from Arab countries that used HPLC-MS/MS (Abdallah et al. 2016, 2017, 2018b; Hammami et al. 2017; Bouafifssa et al. 2018; Al-Jaal et al. 2020), HPLC-HRMS (Al-Jaal et al. 2021), and GC-MS/MS (Juan et al. 2017, 2019, 2020; Oueslati et al. 2018, 2020; Mahmoud et al. 2018; Bouafifssa et al. 2018), carried out their analytical procedures either in laboratories located in Europe and the USA or in collaboration or under the supervision of researchers from analytical laboratories specialized in mycotoxin analysis. Remarkably, until the end of 2021, no paper had presented a method development for mycotoxin analysis, as all the available studies either showed optimization or validation or minor modifications of already published analytical methods by other groups. This observation underscores a genuine need for a capacity-building initiative encompassing equipment or instruments and the expertise of personnel, including technicians and research scientists, to master these sophisticated technologies (Abdallah et al. 2018a).

5. Overview of the most commonly detected mycotoxins in food, feed, human biofluids, and other categories from the Arab world

The collected data were processed to determine the percentage of the most frequently detected mycotoxins (top five) across the constructed 14 categories (**Figure 5**). The number of publications per category was considered during data analysis to ensure a comprehensive overview and avoid misinterpretation. For example, AFB1 was detected in 100% of the survey studies (n = 3) in the oils category. This limited number of publications hinders drawing a solid conclusion about mycotoxins in this category. In general, AFB1 and AFB2 were among the top five most frequently detected mycotoxins. Indeed, AFM1 was the most targeted and detected metabolite in dairy products and as a human biomarker. Additionally, OTA was among the top five mycotoxins in all categories, except in cereal byproducts, legumes and pulses, nuts, and oils.

Interestingly, while multiple mycotoxins ranked among the top five in different food categories, they were not commonly studied in human biofluids. For instance, DON was among the top five mycotoxins detected in 23% and 25% of the total publications in cereals (n = 81) and cereal byproducts (n = 12), respectively. ZEN was found in 25% of the papers from the cereals category (n = 81). Similarly, ENA-1 and ENB-1 were among the top five mycotoxins found in 17% and 33% of cereal byproducts category (n = 12), respectively. Furthermore, PAT was determined in 21% of the publications (n = 29), explicitly targeting PAT in juices and other drinks. In addition to the toxins mentioned above, other main mycotoxins and emerging mycotoxins have not been investigated in human biofluid samples across the Arab world. For example, FB1 (reported in 16 papers) or FBs (sum of FB1 and FB2) (reported in 7 papers) ranked 7th in the cereal grains category, i.e., not found to be among the top five mycotoxins.

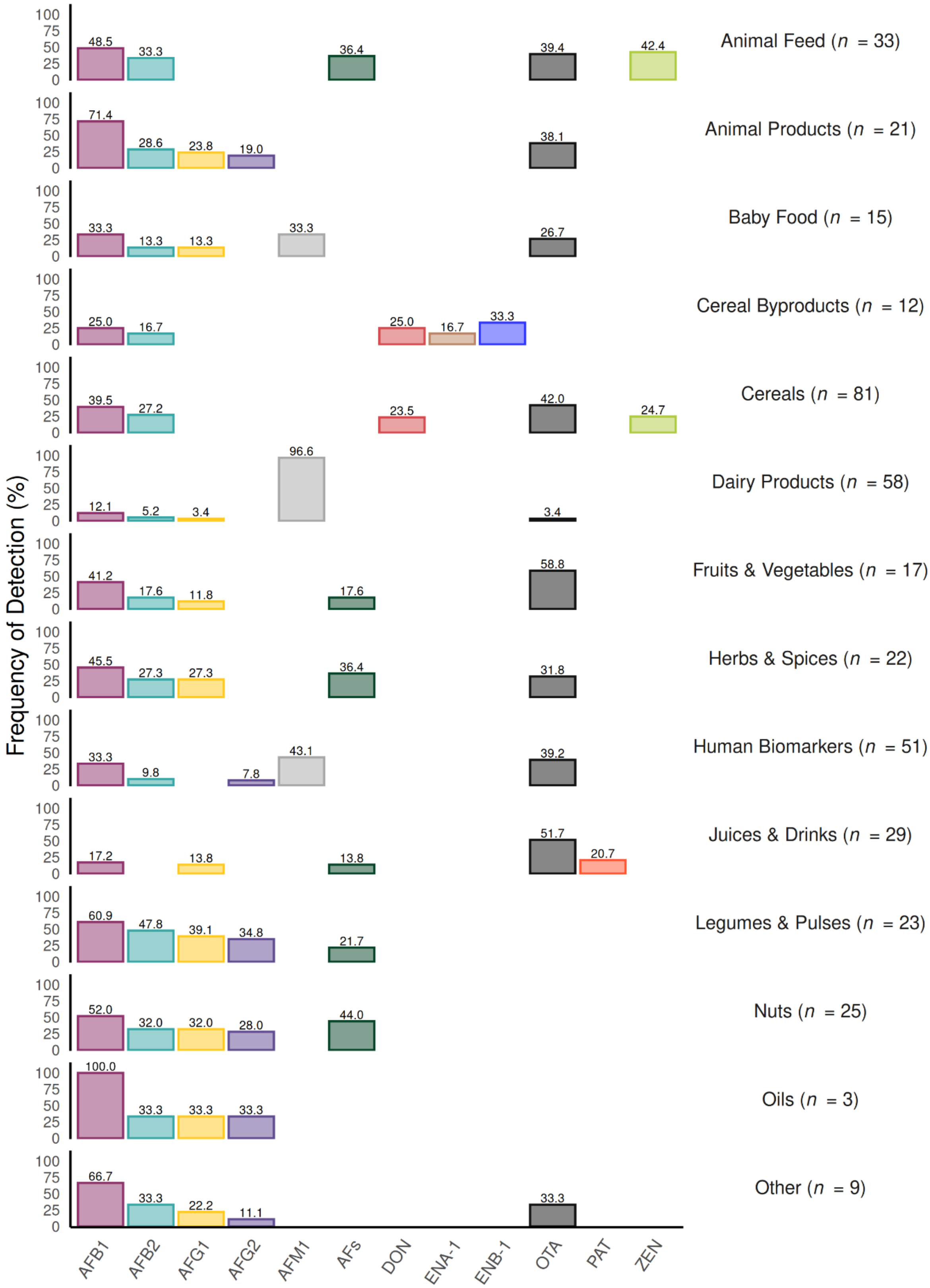

Figure 5: Detection frequency (%) of the commonly detected mycotoxins (top five) in 14 different categories of food, feed, human biofluids, and others across all Arab countries from 1977 to 2021. *n* = number of publications.

Implementation of single mycotoxin biomonitoring, such as AFM1 or OTA, in human biofluids was observed in most of the collected papers (Maaroufi et al. 1995; El-Sayed Abd Alla et al. 2000;

Abdulrazzaq et al. 2002, 2003; El-Sayed et al. 2002) (see the supplementary data). In a cross-sectional study from Egypt, several urine samples (*n* = 98) from pregnant women were collected and analyzed for the presence of AFs (mainly AFM1) and DON biomarkers, revealing a co-contamination in 41% of the samples. However, the two targeted biomarkers were analyzed separately (Piekkola et al. 2012). Multi-mycotoxin biomonitoring was applied in a few studies from Egypt, Qatar and Tunisia (Hatem et al. 2005; Belhassen et al. 2015; Al-Jaal et al. 2020, 2021). Hatem *et al.* investigated the occurrence of multiple AFs biomarkers (B1, B2, G1, G2, M1, M2, B2a, G2a, B3, GM1, P, and aflatoxicol) in blood and urine samples from 70 infants (30 infants suffered from malnutrition disease called kwashiorkor, 30 infants suffered from another malnutrition disease called marasmus and ten healthy infants). The analysis of this group of metabolites was done using TLC, concluding a high correlation with protein-energy malnutrition due to a high prevalence of AFs (especially AFB1) in serum and urine samples of kwashiorkor infants (Hatem et al. 2005). However, the existence of a causal link to AFs remains unclear (Abdallah et al. 2021). Additionally, Al-Jaal *et al*. implemented HPLC-MS/MS and HPLC-HRMS to quantify multiple mycotoxins in serum (19 to 20 mycotoxins) and urine (14 mycotoxins) samples in the Qatari population, respectively. T-2 was the most commonly detected mycotoxin, quantified in six samples out of 46 serum samples (Al-Jaal et al. 2020). In another study, serum (*n* = 412) and urine (*n* = 559) samples from residents of Qatar were collected and analyzed. Among the serum samples, NEO was the most detected metabolite (*n* = 45), while zearalenol metabolites (β-ZEL, *n* = 42 and α-ZEL, *n* = 22) and ROC (*n* = 24) were the most prevalent compounds in urine (Al-Jaal et al. 2021). In Tunisia, ZEN and its five metabolites were quantified in 31 (28%) out of 110 women's urine samples using UHPLC-MS/MS (Belhassen et al. 2015). The existing studies emphasize the need for similar multi-mycotoxin surveys across other Arab countries to establish a comprehensive "mycosome" database in the Arab world.

Figure 6 illustrates the quantitative levels (mean values) of the same top five most frequently detected mycotoxins per category, as depicted in **Figure 5**. Given that most of the collected publications (236 papers out of 306) reported mean values in their findings, this parameter was considered in the analysis. Hence, papers that exclusively reported median or maximum values were excluded, resulting in 258 analyses (total "*n*" in **Figure 6**) for the top five mycotoxins across the 14 categories. The mean values of the commonly detected mycotoxins (top five) in the 14 categories, along with the number of publications of each mycotoxin within each category, are provided in the supplementary data (**Table S1**). As mycotoxin regulations are not standardized across the Arab countries (refer to the following section of this review), the data in **Figure 6** were compared to the European Union (EU) regulations (European Commission 2023), and specific categories are further discussed in the subsequent paragraphs.

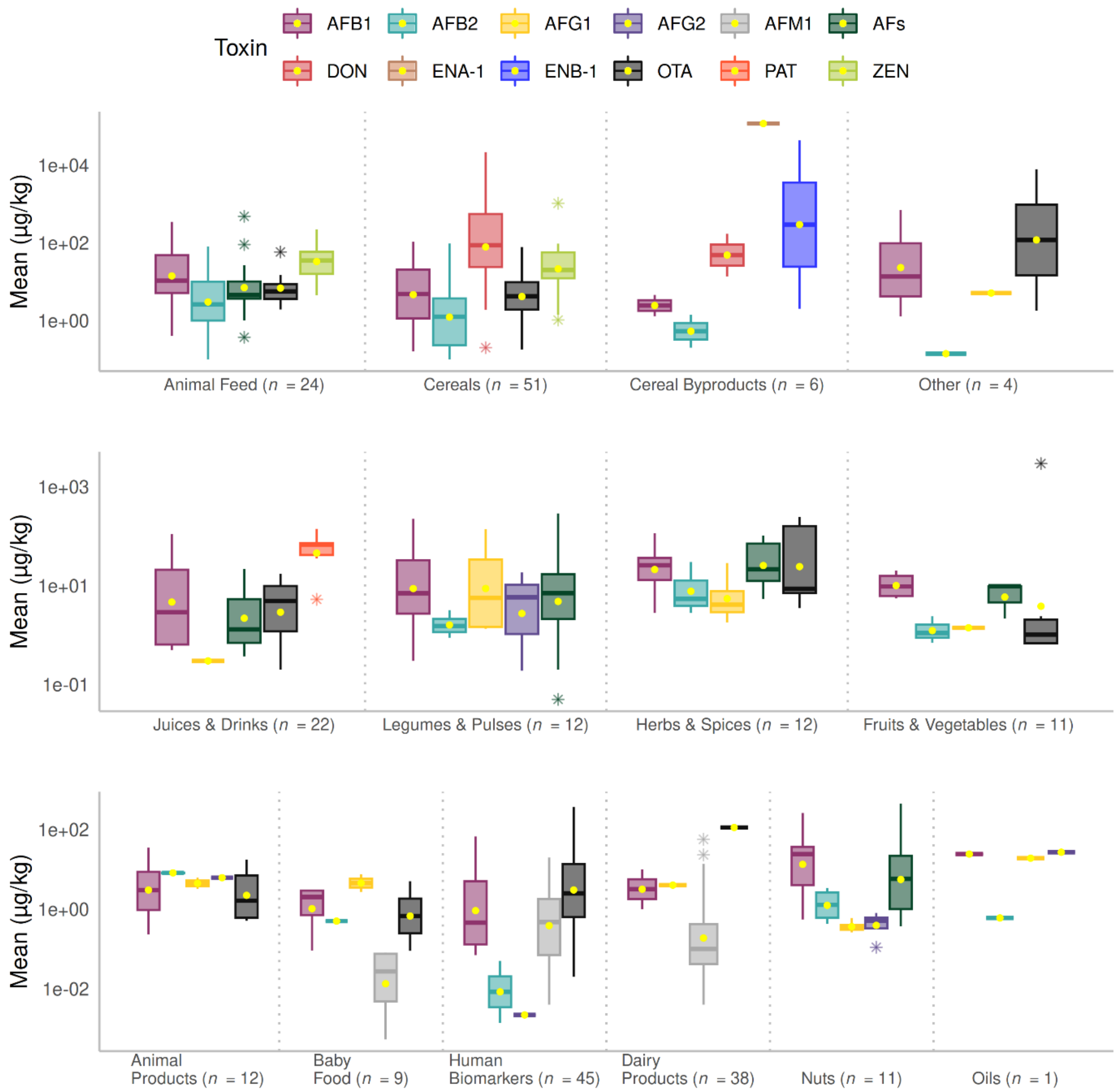

Figure 6: Mean values of the commonly detected mycotoxins (top five) in 14 different categories of food, feed, human biofluids, and other across all Arab countries from 1977 to 2021. Data beyond the ends of the whiskers are called outlying points and are plotted individually. *n* = number of publications.

AFB1 is regulated in both processed and unprocessed cereals and cereal-based products by national and international authorities. The EU has set a maximum permissible level of 2 µg/kg, except for maize and rice, subjected to sorting or other physical treatment (5 µg/kg) (European Commission 2023). As the available data shows (**Figure 6**), the estimated overall mean value of AFB1 in (raw) cereals and cereal-based products from Arab countries is around 17 µg/kg, exceeding the EU maximum permissible level by more than threefold. This could be accepted as AFB1 occurrence in cereals from Egypt (maize and wheat) (Abdallah et al. 2017; Deabes et al. 2018; Hathout et al. 2020), Morocco (processed maize) (Zinedine et al. 2017), and Tunisia (pearl millet, barley, maize, sorghum, rice, and wheat) (Ghali et al. 2008; Oueslati et al. 2012; Jedidi et al. 2017; Houissa et al. 2019) all showed higher concentrations than the EU limits. For example, Hathout *et al.* reported a mean value of 21 µg/kg of AFB1 in 12 wheat samples (out of 36 samples), while Deabes *et al*. detected 20 µg/kg in 37 maize samples (out of 120 samples), both exceeding the EU permissible levels in unprocessed maize by fourfold (Deabes et al. 2018; Hathout et al. 2020). In Tunisia, higher averages of AFB1 concentrations were documented by Houissa *et al.* in pearl millet (106 µg/kg in 19/220 samples), Jedidi *et al.* in maize (47 µg/kg in 4/10 samples collected at harvest time), Oueslati *et al*. in sorghum (47 µg/kg in 3/3 samples), and Ghali *et al*. in sorghum (12 µg/kg in 10/17 samples) and barley (18 µg/kg in 3/25 samples) (Ghali et al. 2008; Oueslati et al. 2012; Jedidi et al. 2017; Houissa et al. 2019). Other papers reported even higher concentrations; however, the mean values were not presented (Wielogorska et al. 2019).

The overall estimated mean concentration of OTA (12 µg/kg) in cereals exceeds the maximum EU level in unprocessed cereals (5 µg/kg). In Egypt, various cereals such as maize, barley, and rice were contaminated with mean values ranging from 14 to 25 µg/kg (El-Sayed 1996). Wheat samples (n = 17) from farm warehouses and rice samples (n = 100) from retail markets in Morocco were contaminated with mean levels of 29 µg/kg and 12 µg/kg, respectively (Hajjaji et al. 2006; Juan et al. 2008a). Additionally, wheat samples (n = 39) from Algeria had an average OTA concentration of 7 µg/kg (Zebiri et al. 2019). Other studies on OTA contamination in Tunisian cereals revealed also high concentrations (**List S1,** supplementary data). Millet samples (19 out of 220) had an average OTA concentration of 69 µg/kg, while various cereals, including barley (41 out of 103 samples), rice (27 out of 96 samples), sorghum (43 out of 113 samples), and wheat (42 out of 110 samples), showed average OTA concentrations ranging from 44 to 117 µg/kg (Zaied et al. 2009; Houissa et al. 2019).

The estimated mean level of DON in cereals (including unprocessed maize, durum wheat, and oats) is approximately 1635 µg/kg, which falls below the maximum EU level of 1750 µg/kg. However, very high concentrations of DON ranging between 14,700 and 30,500 µg/kg were reported in field durum wheat grains collected from five different areas in the North of Tunisia (Bensassi et al. 2010). On the other hand, reports from Algeria (maize, wheat, and rice), Egypt (maize), Jordan (barley, rice, and wheat), Morocco (wheat), Saudi Arabia (wheat), and Syria (wheat) documented DON mean values below 750 µg/kg, the maximum EU level for DON in processed cereals (Salem and Ahmad 2010; Blesa et al. 2014; Alkadri et al. 2014; Abdallah et al. 2017; Mahdjoubi et al. 2020). Similarly, the overall estimated mean value of ZEN in cereals, including maize, from Algeria, Bahrain, Egypt, Morocco, Syria, and Tunisia is approximately 88 µg/kg, which is less than the EU maximum permissible levels in unprocessed maize (350 µg/kg) or other unprocessed cereals (100 µg/kg) (Zinedine et al. 2006; Ghali et al. 2008; Musaiger et al. 2008; Zaied et al. 2012b; Alkadri et al. 2014; Abdallah et al. 2017; Mahdjoubi et al. 2020). Although most of the samples aligned with the permissible levels, notable exceptions were found. For instance, high concentrations of ZEN, with a mean value of 1040 µg/kg, were detected in 15 (30%) maize kernel samples collected from Yemen (Al-Jobory et al. 2017).

The estimated mean value of PAT in the juices and drinks category is approximately 65 µg/kg, surpassing the EU permissible levels set at 50 µg/kg in fruit juices and spirit drinks, and 10 µg/kg in apple juice and solid apple products for infants. Samples of fruit juices, including apple juice, collected from Saudi Arabia (*n* = 120) and Tunisia (*n* = 214) had PAT contamination with total mean values around 67 µg/kg and 89 µg/kg, respectively (Gashlan 2008; Zouaoui et al. 2015). Other surveys also detected PAT at levels higher than the EU permissible limit, although these studies had limited sample sizes, mostly less than 30 samples. OTA in the juices and drinks category has an overall mean value of 7 µg/kg (**List S1,** supplementary data), which exceeds the EU limits in roasted coffee beans and ground roasted coffee (3 µg/kg), as well as soluble (instant) coffee (5 µg/kg) (European Commission 2023). A survey study from Yemen quantified OTA by ELISA in all samples of roasted and green coffees (*n* = 50), showing a mean value of 7 µg/kg (Humaid et al. 2019). Indeed, further surveys are necessary to draw a more solid conclusion for PAT and OTA in this category. In the herbs and spices category, the overall estimated mean values of AFB1 (37 µg/kg), AFs (43 µg/kg), and OTA (85 µg/kg), derived from various surveys conducted across Algeria, Bahrain, Egypt, Lebanon, Morocco, Qatar, Saudi Arabia, and Tunisia, all exceed the EU limits of 5 µg/kg, 10 µg/kg, and 15 µg/kg in mixtures of dried spices, respectively (European Commission 2023).

For dairy milk (the major matrix screened in the dairy products category), the estimated mean value of AFM1 (3 µg/kg) is nearly 60 times higher than the EU maximum permissible level (0.05 µg/kg). Notable surveys on AFM1 in milk are available from Lebanon by Daou *et al*. who detected AFM1 in 59% (*n* = 412) of raw cow milk samples out of 701 samples across the country using HPLC-FLD (Daou et al. 2020). Around 28% (*n* = 196) of the samples were contaminated with AFM1 levels above 0.05 µg/kg. Another study from Saudi Arabia used ELISA to screen 393 samples from various dairy products (white cheese, cream cheese, Kashar cheese, and butter), revealing contamination in 80% of the samples (Waqar Ashraf 2012). In Egypt, AFM1 was detected in all 90 buffalo milk samples analyzed, with 93% of the samples exceeding the EU limit (Shaker and Elsharkawy 2014). Surveys from other Arab countries also reported higher levels of AFM1 in milk and other dairy products.

6. Current legislation on mycotoxins in the Arab world

Regulations regarding mycotoxins in food and feed were established, based on sound scientific evidence, with the aim of safeguarding the public as much as possible from the known harmful impacts of dietary mycotoxin exposure. Searching academic databases and government websites, up to the time of submitting this review article, showed that national and regional legislations or regulations on mycotoxins vary among the Arab countries (**Table 2**). The regulations on mycotoxins seem not to exist or be otherwise unavailable in Comoros, Djibouti, Mauritania, Palestine, and Somalia. In Algeria and

Tunisia, the regulations are limited to AFB1, according to the FAO's database on Food Legislation (FAOLEX). Iraq, Jordan, Sudan, and Syria apply partial adoption of the Codex Alimentarius standards CXS 193-1995, which was released in 1995; revised in 1997, 2006, 2008, and 2009; and amended in 2010, 2012, 2013, 2014, 2015, 2016, 2017, 2018, and 2019 by the Codex Committee on Contaminants in Food (CCCF) (FAO 2004; FAO/WHO 2019). These standards aim primarily to ensure the safety, quality, and fairness of the international food trade. Other missions related to the CCCF include considering methods for sampling, analysis of natural toxins, and developing and elaborating codes of practice to reduce natural toxins in food and feed. The Codex Alimentarius Commission currently has 188 member countries, which includes all the Arab countries except Palestine (observer only). It is also known that the Codex standards are voluntary in nature, and a translation into national legislation or regulations is needed to be enforceable. In Libya, national regulations are provided by the Libyan National Centre for Standardization and Metrology (LNCSM 2010, 2013, 2015). In multiple survey studies conducted in Arab countries, a reference to the EU regulations or FAO website was commonly used when a mycotoxin lacks regulation to assess whether the detected concentrations might pose a public health concern (FAO 2004; European Commission 2006).

For the six Gulf Cooperation Council (GCC) members (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and United Arab Emirates) and Yemen, the GCC Standardization Organization (GSO) has approved their own updated standards for mycotoxins in food and feed. One of the reasons motivating common regulations of mycotoxin and other toxins in food and feed among the GCC countries is the cultivation of their shared community through future-oriented policies of developing a common market. For natural toxins, including mycotoxins, the most recent edition of regulations was approved in 2021 (GSO 193:2021). In that version, the maximum limits for mycotoxins are similar to the EU, except for a few mycotoxins. For example, AFM1 is set at 0.5 µg/kg in milk instead of the 0.05 µg/kg EU maximum limit. Also, there are no specific regulations for AFB1, but the total AFs are considered. Although the standards considered several mycotoxins, important toxins such as ZEN are not included. The available free version of the standards was drafted in a proposed document in 2019 (GCC Standardization Organization 2019). The Saudi Food and Drug Authority (SFDA) has issued maximum limits on mycotoxins in food and feed (SFDA.FD 193:2019), which are similar to the recent standards approved by the GSO in 2021 (SFDA 2019). The Egyptian Food Safety Authority (NFSA) and its Moroccan counterpart, the National Office of Food Safety (ONSSA), are adopting the EU regulations "No 1881/2006" (European Commission 2006; NFSA 2022; ONSSA 2022). In Lebanon, only AFs, AFB1, and AFM1 are regulated in a short list of commodities (**Table 2**) according to the Lebanese Ministry of Agriculture, Decision No. 322/1 Permissible Levels of Aflatoxin in Some Foodstuffs (FAOLEX Database 2004). However, several recent publications from Lebanon stated that the Lebanese Standards

Institution (LIBNOR) follows the EU regulations. The well-known EU regulation No 1881/2006 for setting maximum levels for certain contaminants in foodstuffs has been amended several times, and the most recent one, “EU No 2023/915”, has been published on 25 April 2023 (European Commission 2023).

One of the current fruitful initiatives in food and feed safety in the Arab world is the “Arab Codex Network”. This capacity-building project, funded through the US Codex Office, US Department of Agriculture, is implemented by the Global Food Regulatory Science Society (GFoRSS) in collaboration with the Food Risk Analysis and Regulatory Excellence Platform (PARERA) of the Université Laval in Canada. This initiative aims to enhance the cooperation of all Arab Codex Alimentarius members, including the GSO members, to strengthen Codex competencies in the Arab region and promote standards for food safety and quality. This also facilitates communication between the Arab countries and the Codex Alimentarius Commission. Recently, the Arab Codex Office of the Arab Industrial Development Standardization and Mining Organization (AIDSMO) has been established to lead the organization of coordination meetings of Arab Codex Contact points. Further appreciated efforts include hybrid capacity-building workshops and training on (rapid) methodologies for mycotoxin analysis and control in collaboration with other parties from Arab governments, universities, and industries.

To conclude, although noticeable progress has been achieved to enhance food and feed safety through regulation development, the outcomes on mycotoxin occurrence and research conducted by academic institutions and other organizations do not seem to indicate an abating problem. There is still a long way to go before reaching contemporary international food and feed safety levels in the Arab world. Following the recent progress made in issuing regulations and laws, more Arab countries are expected to adopt the EU regulations and recommendations on mycotoxins and other natural toxins in food and feed. Collaboration between governments, academics, private sectors, and other stakeholders will be crucial to gathering all the information and diverse experiences on this topic. The authors of the present review article hold hopes for future collaborative work among research institutions across Arab countries to conduct large-scale surveys. Establishing research networks focused on mycotoxin research, such as the creation of an Arab Society of Mycotoxicology, could facilitate and coordinate comprehensive studies encompassing the occurrence of mycotoxins and their producing toxigenic fungi, risk assessment, and pre-and post-harvest control. The availability of (multi-)mycotoxin analytical methods will enable the practical enforcement of mycotoxin regulations, though contingent on the accessibility of analytical equipment. This necessitates capacity-building across multiple laboratories in Arab countries. These efforts and other activities will potently defend food security in all countries across the Arab league.

Table 2: Current regulations concerning mycotoxins in various food and feed commodities across the Arab countries

Country	Mycotoxin(s)	Commodity	Limit (µg/kg)	References
Algeria	Total AFs	Peanuts, tree nuts, cereals	20	(FAO 2004)
	AFB1	Peanuts, tree nuts, cereals	10	
		Animal feed	20	
Bahrain*	Total AFs	Cereals, nuts, peanuts, dried fruits (for human consumption)	4	(GCC Standardization Organization 2019)
		Cereals, nuts, peanuts, dried fruits (to be processed)	10	
		Spices and herbs	10	
		Other foods (whole commodity)	20	
		Animal feed-maize (for finishing beef cattle)	300	
		Animal feed (for breeding beef cattle or poultry)	100	
		Animal feed (for immature animals or dairy)	20	
	AFM1	Milk (any type)	0.5	
	DON	Cereals (for further processing)	2000	
		Dry pasta	750	
		Flour derived from wheat, maize, barley	1000	
		Bread, biscuits, cereal snacks, breakfast cereals	500	
		Cereals-based food for infants	200	
	FBs (FB1 + FB2)	Maize (unprocessed)	4000	
		Maize-based breakfast cereals & maize-based snacks	800	
		Maize and maize-based foods for human consumption	1000	
		Maize and maize-based food for infants	200	
	OTA	Cereals (unprocessed) and roasted coffee	5	
		Grape juice	2	
		Spices and herbs	15	
		Licorice	20	
		Licorice extract	80	
		Processed cereal-based food for infants	0.5	

	PAT	Apple juices (including concentrated juice)	50	
		Solid apple products and apple puree (direct human consumption)	25	
		Apple juice and food for infants	10	
Comoros		No available regulations		(FAO 2004)
Djibouti		No available regulations		(FAO 2004)
Egypt [1]	Total AFs AFB1	Almonds and pistachios subjected to sorting	15 12	(FAO 2004; NFSA 2022)
		Almonds and pistachios for direct human consumption	10 8	
		Cereals (unprocessed), tree nuts (except hazelnuts and Brazil nuts), dried fruits (except dried figs)	10 5	
		Cereals, peanuts, oilseeds, tree nuts (except hazelnuts and Brazil nuts), dried fruits (except dried figs) for direct human consumption	4 2	
		Hazelnuts and Brazil nuts, peanuts and oilseeds subjected to sorting	15 8	
		Processed cereal-based foods for infants	- 0.10	
		Spices	10 5	
		Animal and poultry feed	20 10	
	AFM1	Milk and other dairy products	0.05	
		Infant formula and other baby food	0.025	
	OTA	Cereals (unprocessed) and coffee beans	5	
		Processed cereals for direct consumption	3	
		Dried vine fruit and soluble instant coffee	10	
		Processed cereal-based foods for infants	0.5	
		Grape juice and alcoholic beverages	2	
		Spices and herbs	15	
	DON	Durum wheat, maize, oat (unprocessed)	1750	
		Cereals for direct human consumption	750	

		Bread, pastries, biscuits, breakfast cereals	500	
		Cereal-based food for infants	200	
	ZEN	Cereals (unprocessed), except maize	100	
		Maize (unprocessed)	350	
		Cereals for direct human consumption	75	
		Maize for direct human consumption	100	
		Refined maize oil	400	
		Cereal-based baby food	20	
	FBs (FB1 + FB2)	Unprocessed maize	4000	
		Maize (for human consumption)	1000	
		Maize flour, maize meal	2000	
		Maize-based breakfast cereals & maize-based snacks	800	
		Processed maize-based for infant food	200	
	PAT	Fruit juices (including concentrated juice)	50	
		Solid apple products and apple puree	25	
		Apple and cereal-based infant food	10	
		Alcoholic beverages	50	
	CIT	Food supplements based on rice fermented with red yeast *Monascus purpureus*	100	
	Ergot Alkaloids	Milling products of barley, wheat, spelt, oats	100 (to be 50 from July 2024)	
		Cereal-based food for infants	20	
Iraq	Total AFs	Cereals, nuts, and peanuts (further processing	15	(FAO 2004; FAO/WHO 2019)
		Cereals, nuts, peanuts, dried figs (ready-to-eat)	10	
		All feedstuffs	30	
	AFM1	Milk (all types)	0.5	
	DON	Cereals (for further processing)	2000	
		Flour, cereal, cereal snacks for breakfast	1000	
		Cereal-based foods for infants	200	
	FBs (FB1 + FB2)	Maize grain	4000	
		Maize flour or meal	2000	

	OTA	Raw wheat, barley, rye	5	
	PAT	Apple Juice, apple juice ingredients	50	
Jordan	Follow the codex 193 (see Iraq for full regulations)			(FAO 2004; FAO/WHO 2019)
Kuwait*	GCC Standardization Organization (see Bahrain for more details)			(GCC Standardization Organization 2019)
Lebanon [2]	Total AFs AFB1	Peanuts, pecans, almonds, hazelnuts, cashews, pistachios, fruit kernels, dried fruit, cereals (wheat, rice, barley, oat) of all types intended for direct human consumption or for use as an ingredient in foodstuffs	4 2	(FAOLEX Database 2004)
		Fodders and feed additives of all types	20 10	
	AFM1	Milk (all types)	0.05	
Libya [3]	Total AFs AFB1	Nuts, dried fruits, cereals, their products	4 2	(Sassi et al. 2010)
		Animal feed	10 5	
		Spices, tea	10 5	
	AFM1	Milk (all types) Baby food	0.05 0.025	
	OTA	Cereal products Dried fruits Cereals, Arabic coffee beans Cereals for baby food	3 10 5 0.5	
	DON	Wheat durum, maize, oat Cereals for baby food Animal feed (cereal-based)	1750 200 8000	
	FBs (FB1 + FB2)	Unprocessed maize Maize (for human consumption) Cereals for baby food Animal feed (cereals)	4000 1000 200 60000	

Mauritania		No available regulations		(FAO 2004)
Morocco [4]	Total AFs AFB1	Peanuts and other oil seeds, hazelnuts, nuts of Brazil subjected to sorting or other physical treatment	15 8	(ONSSA 2022)
		Almonds, pistachios, and apricot kernels to be subjected to sorting or other physical treatment	15 12	
		Almonds, pistachios, and apricot kernels intended for direct human consumption	10 8	
		Hazelnuts and Brazil nuts intended for direct human consumption or use as an ingredient in foodstuffs	10 5	
		Peanuts and other oil seeds and products derived therefrom for direct human consumption	4 2	
		Maize and rice to be subjected to sorting or other physical treatment	10 5	
		All cereals and all products derived from cereals, including processed cereal products	4 2	
		Dried fruit, other than dried figs, to be subjected to sorting or other physical treatment	10 5	
		Dried fruit, other than dried figs, and products derived therefrom, intended for direct human consumption	4 2	
		Dried figs	10 6	
		Spices	10 5	
		Processed cereal-based foods for infants	- 0.1	
	AFM1	Milk (all types) Infant formulas	0.05 0.025	

	OTA	Unprocessed cereals	5
		Processed cereals, cereal products for human consumption	3
		Roasted coffee beans, including ground (except soluble coffee)	5
		Soluble coffee	10
		Wine and wine fruit	2
		Cereal-based baby food intended for infants	0.5
		Spices	15
	PAT	Fruit juices, concentrated fruit juices as reconstituted, fruit nectars	50
		Apple juice and foods (other than processed cereal-based food) for infants	10
	DON	Raw (unprocessed) maize	1750
		Cereals intended for direct human consumption	750
		Dry pasta	750
		Bread, biscuits, cereal snacks, breakfast cereals	500
		Cereal-based baby food	200
	ZEN	Unprocessed maize	350
		Refined maize oil	400
		Maize intended for direct human consumption	100
		Cereal-based baby food	20
	FBs (FB1 + FB2)	Unprocessed maize	4000
		Maize for direct human consumption	1000
		Cereal-based breakfast cereals, corn-based snacks	800
		Cereal-based food for infants	200
Oman*	GCC Standardization Organization (see Bahrain for more details)		(GCC Standardization Organization 2019)
Palestine	No available regulations		(FAO 2004)
Qatar*	GCC Standardization Organization (see Bahrain for more details)		(Al Jabir et al. 2019)

Saudi Arabia*, 5	GCC Standardization Organization (see Bahrain for more details)			(GCC Standardization Organization 2019; SFDA 2019)
Somalia	No available regulations			(FAO 2004; Wielogorska et al. 2019)
Sudan	AFs	Oil seeds	10	(FAO 2004; FAO/WHO 2019)
	OTA	Wheat	15	
Syria	AFB1	Peanuts, pistachios	5	
	Total AFs	Pulses, mixed nuts, oilseed Baby food Animal feed except cattle Animal feed (cattle)	20 0.05 20 10	
	AFM1	Liquid milk Dried milk	0.2 0.05	
Tunisia	AFB1	Food (All products including cereals and their products)	2	(FAO 2004)
United Arab Emirates*	GCC Standardization Organization (see Bahrain for more details)			(GCC Standardization Organization 2019)
Yemen	GCC Standardization Organization (see Bahrain for more details)			(GCC Standardization Organization 2019)

Total AFs (AFB1, AFB2, AFG1, and AFG2).* GCC is the Gulf Cooperation Council. GCC Standardization Organization members (Saudi Arabia, Qatar, United Arab Emirates, Kuwait, Bahrain, and Oman as well as Yemen), the regulations were drafted in 2019. 1 Egyptian Food Safety Authority (2022). 2 Lebanese Food Normalization Agency 2010 – The Lebanese Standards Institution (LIBNOR). 3 The National Center for Standards and Standards in Libya (2010, 2013, and 2015). 4 The National Office of Food Safety (ONSSA) – Morocco. 5 Saudi Food & Drug Authority (SFDA)-SFDA. FD 193:2019.

7. Conclusion and future perspectives

The current work has been prepared to serve as a valuable resource for researchers, policymakers, and stakeholders concerned with food and feed safety across the Arab League. The review comprehensively addresses mycotoxin contamination within the Arab world, delineating various aspects, such as number of survey studies conducted in each country, annual publication trends, prevalent analytical tools for detection, the adoption of single and multi-mycotoxin detection approaches, alongside the frequency of detection and mean contamination levels of the top five mycotoxins across 14 distinct categories identified in this review (animal feed, animal products, baby food, cereals, cereal by-products, dairy products, legumes and pulses, nuts, spices, fruits and vegetables, juices and drinks, biomarkers, oils, and other).

Data on mycotoxin occurrence may be scarce (e.g., Oman and Somalia) to non-existent (e.g., Djibouti and Mauritania) in some countries. Furthermore, multi-mycotoxin detection strategies are rarely applied in the Arab world, showing a real need for capacity-building initiatives to implement the state-of-the-art technologies for mycotoxin detection. The current literature shows differing mycotoxin profiles among food and feed categories, as well as within human biofluids. Therefore, it is recommended that periodic multi-mycotoxin survey studies, especially focusing on mycotoxin biomarkers, be conducted to obtain a clearer picture of mycotoxin contamination. Such studies will assist in performing exposure and risk assessment studies in humans and investigating whether there is a direct link or association between mycotoxin exposure and incurable diseases like liver and kidney cancers or malnutrition-related diseases.

In recent years, Arab countries have made significant progress in legislation by incorporating more mycotoxins and setting maximum permissible levels across multiple commodities. However, effectively enforcing these regulations hinges on access to analytical procedures, necessitating capacity-building efforts. The data further indicate that several regulated mycotoxins may exceed the maximum permissible levels in food and feed, as set by the EU and Arab countries. This overview requires further investigations to validate the observed trend, aiming to construct a comprehensive database for mycotoxins. Another prospective recommendation to control toxigenic fungi and their toxins in the Arab countries by merging traditional pre- and post-harvest techniques and developing innovative strategies will increase the productivity of cultivated land by avoiding the destructive phytopathogenic effects of toxigenic fungi on crops, ensuring less contaminated food and feed. This is crucial, as most Arab countries are developing, and mycotoxin contamination poses a significant obstacle to achieving food self-sufficiency.

Supplementary information

- **Figure S1**: Alluvial diagram showing the number of publications per year in each country
- **Table S1**: Mean values of the commonly detected mycotoxins (top five) in 14 different categories with the number of publications of each toxin within each category.
- **List S1**: List of publications/per country collected and used in the current work.

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Author contribution

Conceptualization: M.F.A. Data collection, processing, analysis, and visualization: M.F.A, M.G, D.A, F.Z, N.N.E, O.M, S.A, S.M.M. Writing the original draft: M.F.A. Contribution to data analysis, design of the figures, and critical editing of the manuscript: K.D.R, S.Y, G.B.G, E.V. All the authors have contributed significantly to the work.

Data availability

The corresponding author can provide access to raw and processed data upon request.

Declarations

Conflict of Interest: The authors declare no competing interests.

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