Regulatory Toxicology and Pharmacology 164 (2026) 105966

Contents lists available at ScienceDirect

Regulatory Toxicology and Pharmacology

journal homepage: www.elsevier.com/locate/yrtph

Exposure and disease burden of fumonisins and aflatoxins from sorghum consumption in Ethiopia

J.A. Sadik [a,b,*], N. Fentahun [c], I.D. Brouwer [d,e], M. Tessema [f], H.J.van der Fels-Klerx [a,g,**]

[a] Business Economics Group, Wageningen University and Research, P.O. Box 8130, 6700 EW, Wageningen, the Netherlands
[b] Faculty of Chemical and Food Engineering, Bahir Dar Institute of Technology, Bahir Dar University, P.O. Box 26, Bahir Dar, Ethiopia
[c] Department of Nutrition and Dietetics, College of Medicine and Health Sciences, Bahir Dar University, P.O. Box 79, Bahir Dar, Ethiopia
[d] Division of Human Nutrition and Health, Wageningen University and Research, P.O. Box 17, 6700 AA, Wageningen, the Netherlands
[e] International Food Policy Research Institute, Washington DC, USA
[f] Nutrition and Food Science Research, Ethiopian Public Health Institute, Addis Ababa, Ethiopia
[g] Wageningen Food Safety Research, Wageningen University and Research, Akkermaalsbos 2, 6708 WB, Wageningen, the Netherlands

ARTICLE INFO

Handling Editor: Dr. Martin van den Berg

Keywords:
Mycotoxin
Exposure
Hepatocellular carcinoma
DALY
Ethiopia

ABSTRACT

Studies on mycotoxin exposure from sorghum consumption and related public health risk estimation are rarely available in Ethiopia. The aim of this research was to assess fumonisin and aflatoxin exposure of adults through sorghum consumption in the Amhara National Regional State (ANRS) and at national level in Ethiopia and to estimate related health risks. Data on fumonisin and aflatoxin concentrations in sorghum samples were collected from a survey and literature. Estimated fumonisin exposure in the ANRS and at national level were below the FAO/WHO limit of 2000 ng/kg bw day to be considered a health concern. The estimated aflatoxin exposure levels in the ANRS and at national level fall below the Margin of Exposure value of 10000, indicating potential health concern. The incidence of hepatocellular carcinoma due to aflatoxin exposure in the ANRS ranges from 0.0003 to 0.017 while at national level, it ranges from 0.181 to 8.47 (per100.000 persons/year). The related disability-adjusted life years estimates for the ANRS and at national level ranged from 0.0003 to 0.019 and 0.204 to 11.230, respectively. Aflatoxin exposures were driven more by sorghum intake than aflatoxin contamination. Dietary intervention could further reduce the health risk estimates.

1. Introduction

Mycotoxins are metabolites produced by certain species of fungi. The most well-known mycotoxins which occur in food are aflatoxins, fumonisins, ochratoxins, patulin, deoxynivalenol, and zearalenone (Abhay K. et al., 2023). Aflatoxins and fumonisins are the major mycotoxins known to cause a public health burden worldwide (Wu et al., 2014). Aflatoxins can lead to liver injury after acute exposure and cancer due to chronic exposure. Aflatoxins also reduce weight gain in children, leading to stunting after chronic exposure (Braun and Wink, 2018). The major aflatoxins are aflatoxin B1 (AFB1), aflatoxin B2 (AFB2), aflatoxin G1 (AFG1) and aflatoxin G2 (AFG2) (Okechukwu et al., 2024). From these four, aflatoxin B1 is the most potent mycotoxin, and its health concern is of greatest concern (Sandoval et al., 2019). AFB1 is hydroxylated to aflatoxin M1 (AFM1) (Okechukwu et al., 2024; Wu et al., 2014) which is seen in cow's milk. Simultaneous exposure to hepatitis B virus in addition to aflatoxin exposure increases the risk of hepatocellular carcinoma (Sandoval et al., 2019; Wu et al., 2014). Fumonisin intake is associated with brain and esophageal cancer, renal and liver toxicity (Bucci et al., 1998), and neural tube defects (Marasas et al., 2004; Wu et al., 2014). The major types of fumonisins are fumonisin B1 (FB1), fumonisin B2 (FB2), and fumonisin 3 (FB3) (Ren et al., 2011). Simultaneous exposure to aflatoxins and fumonisins would exacerbate the mycotoxin health burden on humans (Nikiéma et al., 2004). One of the most used methods to estimate the burden of dietary exposure to food safety hazards is disability-adjusted life years (DALY) where one DALY represents the one year of healthy life lost (Gibb et al., 2015). WHO estimated the burden of disease related to aflatoxins in Africa at 15 DALY per 100,000 persons. To compare, aflatoxins are responsible for 0.5 DALYs per 100,000 in Europe (Gibb et al., 2015).

* Corresponding author. Business Economics Group, Wageningen University and Research, P.O. Box 8130, 6700 EW, Wageningen, the Netherlands.
** Corresponding author. Business Economics Group, Wageningen University and Research, P.O. Box 8130, 6700 EW, Wageningen, the Netherlands.
E-mail addresses: sadik.awol@wur.nl (J.A. Sadik), ine.vanderfels@wur.nl (H.J.van Fels-Klerx).

https://doi.org/10.1016/j.yrtph.2025.105966
Received 11 July 2025; Received in revised form 25 August 2025; Accepted 12 October 2025
Available online 14 October 2025

Sorghum (*Sorghum bicolor* L. *Moench*) is one of the staple food grains in Ethiopia (Atnkut et al., 2025; Mohammed et al., 2022). In the year 2020/21, sorghum was the fourth most produced cereal in the country, next to maize, wheat and teff. In that year, about 4.8 million tons of sorghum grain was produced (Central Statistics Authority of Ethiopia (CSA, 2020/21). In areas of Ethiopia experiencing moisture stress, including those considered in this research, sorghum is the most widely produced and consumed crop (Ministry of Agriculture (MOA, 2020). According to FAOSTAT Food Balances (2022), about 3.8 million tons of sorghum was used for human consumption in 2022 nationally, supplying about 209 kcal/capita/day. Sorghum is mainly used to produce *injera* (a flat pancake-like product) for human consumption. Next to teff, sorghum is the most suitable cereal to produce a good quality *injera* (Baye et al., 2013; Fox et al., 2020; Mohammed et al., 2022; Yetneberk et al., 2005). It is also used to produce complementary foods for young children (Beyene et al., 2016) and to produce local alcoholic beverages such as *tella* and *areki* (Atnkut et al., 2025; Derese et al., 2018). The use of sorghum to produce *injera* has been increasing in recent years due to the rising trend of the market price of teff (Fox et al., 2020).

Despite its importance as a staple food in Ethiopia, sorghum can be contaminated with mycotoxins, even to concentrations beyond regulatory limits (Chala et al., 2014; Mohammed et al., 2022; Ssepuuya et al., 2018; Taye et al., 2018). For instance, Ssepuuya et al. (2018) reported the presence of aflatoxins B1, B2, G1, G2 concentrations ranging from 3 to 323 μg/kg in sorghum samples collected from farmers households and local markets in Ethiopia in 2012/2013. Mycotoxin concentrations in part of the samples exceeded national and international regulatory limits, indicating that mycotoxin presence in sorghum can pose a public health problem in the country. In another research, Mohammed et al. (2022) reported 79 mycotoxins in sorghum samples collected from farmers' households in eastern Ethiopia. The list included both aflatoxins and fumonisins. The presence of conducive climatic conditions in Ethiopia for fungal growth together with the underdeveloped nature of sorghum value chain practices favorable for fungal infection (Mohammed et al., 2022; Taye et al., 2016, 2018) as well as the low level of awareness of farmers about mycotoxins and their control (Beyene et al., 2016) have been mentioned as a reason for the mycotoxin contamination.

An appreciable number of mycotoxin exposure studies have been conducted in Ethiopia. These studies have been conducted by using biomarker studies for mycotoxins in blood/plasma, urine and breast milk (Ayele et al., 2022; Boshe et al., 2020; Mesfin et al., 2023; Mulisa et al., 2024; Tessema et al., 2021). Although these studies did not indicate whether the results were due to acute or chronic exposure, the findings of most of these studies indicated that mycotoxin exposure is a public health problem in Ethiopia and suggested the implementation of appropriate interventions to reduce the associated problems. However, biomarker-based studies are known to provide more reliable information for mycotoxin exposure than dietary intake-based studies, the dietary intake-based studies can provide better directions to intervention to reduce the problem. In addition, the limitation to the above studies is that the quantitative public health burden related to mycotoxin exposure, such as hepatocellular carcinoma (HCC) and DALY was not estimated. A quantitative estimate of the public health burden is more important information to public health policymakers than exposure information (Gibb et al., 2015). In addition, understanding the risk factors for mycotoxin exposure and related health burden helps to identify priority areas for intervention.

This study aimed to assess the aflatoxin and fumonisin exposure of adults through sorghum consumption, and to assess the related public health burden. The risk assessment was conducted for Northwest Ethiopia and at national level.

2. Materials and methods

2.1. Mycotoxin data collection

Data from a previous study on mycotoxin concentration in 240 sorghum samples grown in northwest Ethiopia in the 2022 cropping season, collected at harvest and after six months of storage, was used. Details on the selection of the sampling locations, sample size, sampling, sample preparation, and mycotoxin analysis are available in Sadik et al. (2025) and Sadik et al. (2025b, in press).

2.2. Management of left censored data

Fumonisin and aflatoxin concentrations that are lower than their LOD values were managed according to the EFSA (2010) recommendations with slight modifications. Based on EFSA (2010), when the proportion of samples with results less than the LOD values is above 80 % of the total samples (left censoring data), estimation of the statistical mean, median, and standard deviation is considered not practicable. That is because for data where more than 80 % of the data is left censored, the mean does not ensure the reliability and comparability of the results. It also does not provide a realistic description of food contamination and exposure assessment, thus not providing sound information on which to base decisions (GEMS/Food-EURO, 1995). For such cases, a simple estimate of the mean can be conducted by producing two estimates - one is by substitution of all the non-detectable results by a value of zero (lower bound) and the other is by substitution of all the non-detectable results by the numerical value of the LOD (upper bound). In our case, we used the average values of both lower bound and upper bound values for risk assessment because the LOD values for the fumonisins (1.5 ng/g) and aflatoxins (0.06 ng/g) were low.

2.3. Sorghum processing practices for regular food preparation

Data about sorghum processing practices was collected through a face-to-face interview with the person responsible for food preparation in 120 households. Interview data were collected from the end of March to mid-April 2023. The basic sorghum *injera* processing questionnaire was adopted from Yetneberk et al. (2005) and Baye et al. (2013) (Supplementary Fig. 1). The questionnaire was initially developed in English language and was translated into the local language (*Amharic*). Ethical approval for the interview was obtained from Bahir Dar University Institutional Review Board (Protocol number 12/IRB/23) before respondent data collection. Written Informed Consent was received before the interview.

2.4. Mycotoxin exposure

All the respondents mentioned regularly using sorghum grain to prepare *injera* for their family consumption (Supplementary Table 1). Therefore, sorghum *injera* (hereunder referred to as '*injera*') was used to estimate the mycotoxin exposure and the related public health risk.

Sorghum processing can lead to mycotoxin reduction of the foods, with variability in reduction depending on the processing conditions (Adebo et al., 2019; Fandohan et al., 2005; Matumba et al., 2019; Udovicki et al., 2019). Since all the respondents in the present study mentioned milling sorghum and *teff* grains without any prior decortication (without dehulling), we assumed the whole milling of these grains does not have an impact on mycotoxin reduction. In *West Belesa* woreda, all the respondents mentioned blending *teff* with sorghum for making *injera*. Woreda is an administrative division that functions like a district in Ethiopia. It is one level below a zone and one level above a kebele (village or ward). Previous research by Geremew et al. (2018) and Ayalew et al. (2006) reported the occurrence of mycotoxins in *teff* grain/flour samples. Therefore, we assumed the two grains are similarly vulnerable to mycotoxin contamination, and as a result, blending *teff* to

sorghum has no impact in reducing mycotoxin concentration due to dilution effects. Further, the temperature and time of baking to obtain optimal quality *teff injera* range from 230 to 260 °C for 2–3 min (Bikila et al., 2024). Because of the very short *injera* baking time, we assumed that baking injera does not reduce the concentration of mycotoxins. The local *injera* processing practices, complemented with literature data for the extent of mycotoxin reduction during sorghum processing, were used to calculate the mycotoxin concentration in the *injera* (*FC*), by adopting the method that was used for mycotoxin reduction in maize products (Udovicki et al., 2019):

$$FC = IC \times (100\,\% \times RF1 \times RF2 \times RF3) \quad \text{Eq. 1}$$

where: *IC* refers to the initial mycotoxin concentration in the sorghum grain. *RF1* refers to the mycotoxin remaining after reduction due to the combined effect of manual sorting and windowing, *RF2* refers to the mycotoxin remaining after reduction due to dilution effect of water addition, and *RF3* refers to the mycotoxin remaining after reduction due to 2–3 days natural fermentation. The average reduction factors obtained from literature are given in Supplementary Table 2.

Monte Carlo simulation was used to estimate the mycotoxin exposure so as to consider the natural variation in mycotoxin occurrence, sorghum intake and body weight (Liang et al., 2021). Total aflatoxins (sum of AFB1, AFB2, AFG1 and AFG2) and total fumonisins (sum of FB1, FB2 and FB3) were individually used in the simulation applying 100,000 iterations using Eq. (2) according to (Udovicki et al., 2019).

Exposure to aflatoxin and fumonisins was determined for adults by calculating the Estimated Daily Intake (EDI) of the mycotoxins due to *injera* intake (Eq. (2)) based on (Udovicki et al., 2019).

$$EDI\ (ng\,kg^{-1}bw\ day) = \frac{average\ injera\ consumption\ (g/day) \times mycotoxin\ concentration\ (ng/g)}{body\ weight\ (kg)} \quad \text{Eq 2}$$

The best fit distribution models for the aflatoxin and fumonisin occurrence data were selected based on the Model-then-Add approach (MTA) using the @Risk software (Andrade et al., 2020).Accordingly, the Pareto statistical distribution was used for both aflatoxins and fumonisins (Supplementary Fig. 2). This distribution was selected based on the Akaike Information Criteria, which is calculated from the log-likelihood function and takes into account the number of parameters of the fitted distribution using the @Risk software. The sorghum intake data for the Amhara National Regional State (ANRS) and at the national level in Ethiopia were obtained from the National Food and Nutrition Strategy survey (Ethiopian Public Health Institute, ((EPHI, 2025)). (Supplementary Table 3). This survey was conducted at a national level from 2021 to 2024, and the ANRS data was collected between 2021 and 2022. We used sorghum intake data collected from women of reproductive age (14–59 years old) using a 24-h recall method. A total of 944 and 10,006 women of this age were surveyed for the ANRS and nationally, respectively. Details of the survey, including the sample size, the sampling method and the quantitative dietary assessment, are available in the Ethiopian Public Health Institute (2025) report. We assumed that the sorghum intake of adult women and men was the same. We assumed all the sorghum intake is in the form of *injera*. The intake data showed a large variation between mean and median values, both in the ANRS and at national level, thus data were not normally distributed. In addition, from the large standard deviation values, we understand that the sorghum intake level is widely varying among the consumers. Therefore, we applied a statistical distribution to account for variability in consumption. A triangle distribution was used for sorghum intake by using the minimum intake (the 2.5 percentile intake), the most likely intake (the median), and the maximum (97.5 percentile intake) values. Further, the mean intake quantities for both the ANRS and the National level were much higher than the respective median intake levels, implying that the raw intake data were skewed to the right. Therefore, the 2.5 and the 97.5 percentile intake quantities were calculated from a log transformed mean and standard deviation of the intake data. The 2.5 % and 97.5 % intake values obtained for the ANRS were 71 g and 1039 g, respectively; while for the National level, the values were 77 g and 1014 g, respectively (Supplementary Fig. 3).

For body weight, the mean and median values were similar for the ANRS and for the National level, indicating data for both the ANRS, and at the National level were normally distributed (Supplementary Table 3; Supplementary Fig. 4). In addition, because the food consumption survey was conducted at national level, we assumed the sample mean and standard deviation of body weight for the national level data would represent the population mean (μ) and variance (σ2), respectively.

For the mycotoxin exposure assessment at national level, we used mycotoxin occurrence data from literature. From a literature search, six articles were obtained on the occurrence of mycotoxins in sorghum in Ethiopia (Supplementary Table 4). However, the fumonisin and aflatoxin occurrence data reported by Ssepuuya et al. (2018) was used in this study. This study was selected because the samples in this study were collected from a survey conducted at national level, while the other studies were conducted in a specific part of Ethiopia. In addition, the other articles missed at least one of the specific aflatoxins or fumonisins required in the current study, which made it difficult to determine the total aflatoxins and total fumonisins. Further, Ssepuuya et al. (2018) collected the samples from a newly harvested and stored grain in farmers households as well as from the market, making the results more realistic since the different stages of the sorghum value chain were considered. For the other studies, samples were collected only from the farmers' households or from controlled experiments.

2.5. Sensitivity analysis

Sensitivity analysis was conducted graphically using a tornado plot to investigate how the percent changes in the input variables (aflatoxin concentration, sorghum intake and body weight) influence exposure (EDI) based on the @Risk software instructions ((Risk and decision analysis platform for Microsoft Excel, version 8.8.1, Palisade Company LLC, NY, USA) according to Herojeet et al. (2023).

2.6. Risk characterization

The public health risk for fumonisin exposure was evaluated by comparing the estimated EDI value with the provisional maximum tolerable daily intakes (TDI) value of 2000 ng/kg bw day (FAO/WHO, 2017). For aflatoxins, which are both carcinogenic and genotoxic, there is no Tolerable Daily Intake (TDI) (EFSA, 2020). The risk of exposure to aflatoxins was estimated by determining the Margin of Exposure (MOE), the risk of incidence of hepatocellular carcinoma (HCC), and the disability-adjusted life years (DALY) (Mihalache et al., 2024).

2.6.1. Risk of characterization for aflatoxin

2.6.1.1. Margin of exposure (MOE). MOE is a dividend of the BMDL10 (benchmark dose lower limit), a value of aflatoxin derived from animal

studies (400 ng/kg bw/day) by the EDI. MOE value below 10000 is an indicator for the presence of public health concern (FAO/WHO, 2014).

2.6.1.2. Liver cancer risk estimation. The average cancer potency of AFB1 (Pcancer) was estimated considering the proportion of individuals having hepatitis B surface antigen positive (HBsAg+) and hepatitis B surface antigen negative (HBsAg-) from the total population (FAO/WHO, 2017) (Eq (3)). The prevalence of HBsAg+ in rural Ethiopia (9.7 %) and the pooled prevalence of HBsAg + at national level (9.4 %) reported for ages above 15 years in Ethiopia (Ethiopian Ministry of Health (MOH, 2021) were used for the determination of *Pcancer* in Amhara regional national state and at national level, respectively.

$$Pcancer = 0.01 \times HBsAg^{-} + 0.3 \times HBsAg^{+} \quad \text{Eq. 3}$$

The risk of incidence of hepatocellular carcinoma (HCC) (case number/100,000 persons/year) was simulated using Eq (4) (Udovicki et al., 2019):

$$Risk\ of\ HCC = Pcancer \times EDI \quad \text{Eq. 4}$$

According to Sandoval et al. (2019), estimation of extra cancer cases (HCC) for a lifetime exposure to aflatoxin, and its expression per million population, is a more common way of expressing HCC results in toxicology research. To estimate the risk of lifetime exposure to aflatoxins, the HCC result obtained from equation (4) was multiplied by the average life expectancy years for Ethiopians, which is 67.8 years (WHO, 2024; https://data.who.int/countries/231), and by a factor of 10 (Sandoval et al., 2019). For lifetime risk estimation, we assumed that individuals' EDI remains constant throughout their lifetime.

2.6.1.3. Estimation of DALY of aflatoxins. DALY (Disability-adjusted life years) due to aflatoxin exposure was estimated by using the HCC result obtained from Eq. (5) and additional data obtained from the Global Cancer Observatory (GCO)(231-ethiopia-fact-sheet.pdf). From the GCO database, the total number of new liver cancer cases for both sexes and all ages in Ethiopia in 2022 were 2798 and the total number deaths due to liver cancer were 2683. This would mean that the death rate from the incidence of HCC cases was 95.9 % (2.683/2.798 = 0.956). The DALY per capita at national level due to the incidence of HCC from aflatoxin exposure was obtained by using the equation adopted from Mihalache et al. (2024). Although morbidity is also important to be considered for the DALY calculation (Gibb et al., 2015), morbidity data related to aflatoxin exposure in Ethiopia, such as numbers of illness cases, the duration of illness is not available to date.

$$DALY = 0.959 * incidence\ of\ HCC \quad \text{(Eq.5)}$$

2.7. Statistical data analysis

The data distribution models and the Monte Carlo simulations were conducted by using the @ Risk software (Risk and decision analysis platform for Microsoft Excel, version 8.8.1, Palisade Company LLC, NY, USA). The random values of the input variables (aflatoxin/fumonisin concentrations, sorghum intake and body weight) obtained from the statistical distribution models of the respective data were used for the simulations.

3. Results

3.1. Occurrence of aflatoxins and fumonisins

Fumonisins were detected above LOD in 32 samples (13.3 % of the total) while aflatoxins were detected above LOD in 5 samples (2.1 % of total) (Table 1). Shapiro-Wilk test result indicated that neither the aflatoxin nor the fumonisin data were normally distributed (P values = 0.000). In addition, the skewness test indicated that both aflatoxin and fumonisin data were highly skewed to the left (P = 0.000).

Table 1
The occurrence of fumonisin and aflatoxin in sorghum grain in Northwest Ethiopia in 2022 cropping season.

Mycotoxin	LOD (ng/g)	LOQ (ng/g)	Proportion of samples > LOD (%)	Conc range (ng/g)	Reference
Aflatoxin	0.06	0.15	2.1	LOD-29.19 (mean = 0.37 ± 2.29)	This study
Fumonisin	1.5	3.0	13.3	LOD-81.40 (mean = 4.19 ± 8.20)	This study
Aflatoxin	Not given	Not given	Not given	93.32[a]	Ssepuuya et al. (2018)
Fumonisin	Not given	Not given	Not given	178.9[a]	Ssepuuya et al. (2018)

[a] Mean values calculated from the occurrence data of the individual aflatoxins/fumonisins. We assumed a worst-case scenario where the reported mean values for the individual mycotoxins occur in the same samples (thus the mean results are additive). These values are used for risk assessment at national level.

3.2. Fumonisin and aflatoxin exposure

The simulated results for fumonisin and aflatoxin exposure are presented in Fig. 1. The fumonisin exposure ranges from 0.10 to 14.78 ng/kg bw day in the ANRS, and from 7.47 to 299.16 ng/kg bw day at the national level. These exposure levels are much lower than the maximum exposure limit of 2000 ng/kg bw day set by FAO/WHO (2017) indicating that the associated public health risk is negligible. The aflatoxin exposure ranges from 0.007 to 0.267 in the ANRS, and from 5.08 to 300.00 at national level (Fig. 1). The different percentiles of aflatoxin exposures and related public health risk estimates are shown in Supplementary Table 5.

The simulated MOE results obtained for the aflatoxin exposure are presented in Fig. 2. Most of the estimated results in the ANRS, and all the results at national level were below the MOE value of 10000, a maximum value that is used as a cut-off point for the presence of public health concern for aflatoxin based on EFSA (2020).

The estimated incidence of HCC due to aflatoxin exposure in the ANRS ranges from 0.0003 to 0.017 while at national level, the HCC ranges from 0.181 to 8.47 (per100,000 persons/year) (Fig. 3). For a lifetime aflatoxin exposure, the incidence of new HCC cases per capita would be 0.2 to 11.5 in the ANRS, and 122.7 to 5742.66 at national level (per million persons), respectively. The related DALY for lifetime aflatoxin exposure in the ANRS and at national level ranged from 0.2 to 11.05, and 117.69 to 5489.98 (per million), respectively. For the total of 125 million population in Ethiopia in 2022 (https://data.who.int/countries/231), the related total DALY in the year 2022 was estimated to be 216.96 to 10,121.64.

3.3. The contribution of study variables to aflatoxin exposure

The pattern of aflatoxin exposure changes as the aflatoxin concentration in the grain, daily sorghum intake and assumed average body weight change are shown in the tornado plot (Fig. 4). The change in exposure showed a steeper line (indicating a slightly linear relationship) for change in sorghum consumption than for aflatoxin concentration and body weight, indicating sorghum intake having a greater impact on aflatoxin exposure than the other variables.

4. Discussion

The objective of this research was to assess the aflatoxin and fumonisin exposure and related public health risks from sorghum consumption in the ANRS and at national level in Ethiopia.

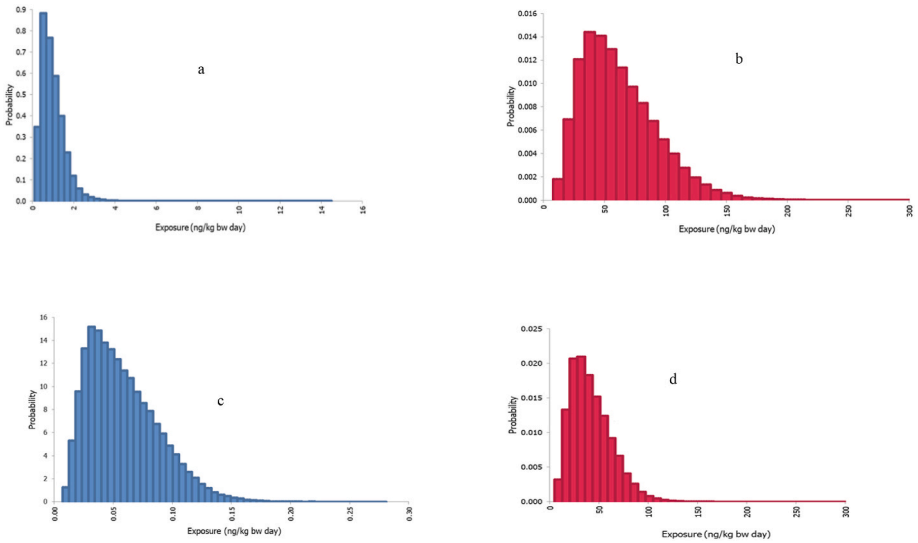

Fig. 1. Fumonisin exposure in the ANRS (a) and at National level (b); and aflatoxin exposure in the ANRS (c) and at national level (d).

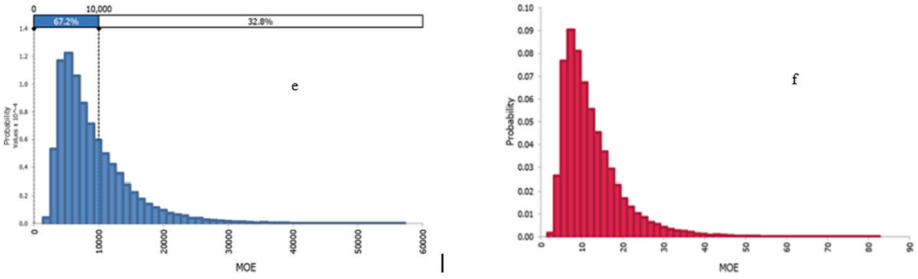

Fig. 2. MOE in the ANRS (e) and at national level (f).

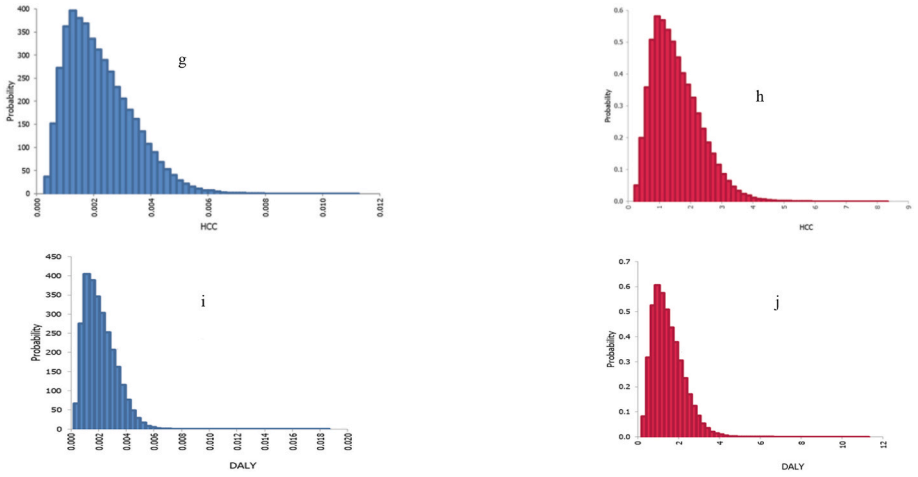

Fig. 3. HCC in the ANRS (g) and National level (h); and DALY in the ANRS (i) and at national level (j).

Compared to the FAO/WHO (2024) limits of 10 ng/g for aflatoxin and 4000 ng/g for fumonisin, only two of the samples (0.8 %) bypassed the regulatory limit for aflatoxins, while none of the samples bypassed the limit for fumonisin. The concentrations of the two samples, which exceeded the limit for aflatoxin, were 18.34 and 29.25 (ng/g). Apart from the fact that there is no TDI set for human aflatoxin exposure due to its genotoxic and carcinogenic nature (EFSA, 2020), the exposure in the ANRS can be taken as low for subsistence farmers situations who apply traditional practices to grow and store sorghum. However, the low levels of fumonisin and aflatoxin concentrations in the ANRS seem to be achieved from farm agronomic practices on the use of pesticides and insecticides, during the growth and storage period of sorghum (Sadik et al., 2025) which probably pose additional public health risks beyond those posed by the mycotoxins themselves. Therefore, it would be interesting to study the extent of pesticide residues in sorghum and their related public health risks as well.

The aflatoxin and fumonisin exposure levels obtained in our study are lower than a previous similar study by Ssepuuya et al. (2018).

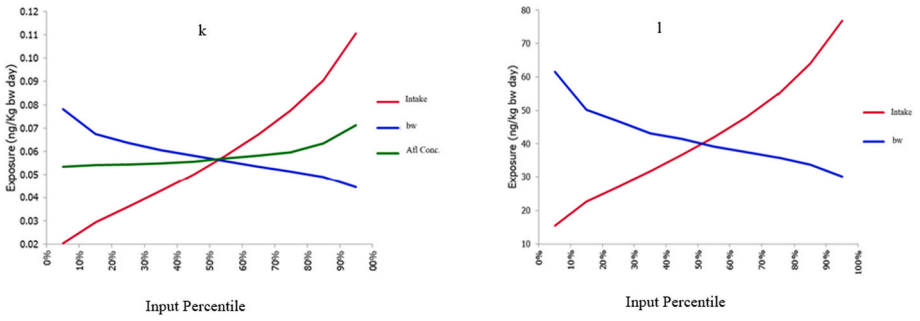

Fig. 4. The impact of aflatoxin concentration, sorghum intake and assumed average body weight on aflatoxin exposure in the ANRS (k) and at national level (l). In Fig. 4l, the aflatoxin concentration is not shown because we used a single parameter for aflatoxin concentration (mean) for exposure estimation at national level.

Ssepuuya et al. (2018) deterministically estimated the fumonisin and aflatoxin exposure from sorghum consumption at national level in Ethiopia for a sorghum intake of 69 g/d and for a 60 kg body weight. Like our finding, the estimated fumonisin exposure (50–700 ng/kg bw/day) was lower than the EFSA (2018) limit of 1000 ng/kg bw day. On the other hand, the estimated aflatoxin exposure (5–100 ng/kg bw day) indicated associated health concerns. Our exposure estimates are much lower than Ssepuuya et al. (2018) partly because we applied processing reduction factors to estimate the EDI, thus the concentrations in food products were different. He probability of aflatoxin exposure to be a priority for risk management (the MOE value to be less than 10000), was about 96 % and 100 % in the ANRS and at national level, respectively (Fig. 2).

Because the mean value for sorghum intake in the ANRS (450g) estimated from the statistical distribution (Supplementary Fig. 3) was higher than the actual mean value of 344 g, our simulation result seems to be overestimating the actual aflatoxin exposure. We therefore also deterministically calculated the aflatoxin exposure values for the actual mean and median intake levels in the ANRS. The results obtained were 0.124 ng/kg bw/day and 3230, for exposure and MOE, respectively (Supplementary Table 6). The values show the presence of health concern as the simulated results.

The median aflatoxin exposure at national level in our study (38.14 ng/kg bw day) is in the range of aflatoxin exposure from sorghum consumption in Mali (2–133 ng/kg bw day), but much lower than the exposure level in Niger (706–2221 ng/kg bw day) (Falade et al., 2022), and higher than in Uganda (19 ng/kg bw day) (Wokorach et al., 2021). This difference could be due to the possible variations in climatic conditions, sorghum agricultural production and storage practices, intake as well as variations in the body weight of adults among these countries. The associated HCC risk predicted for Ethiopia is also lower than in Mali and Niger. Besides to variations in aflatoxin exposure, the lower prevalence of Hepatitis B virus infection in Ethiopia (9.4 % a) (MOH, 2021) than in Mali (20 %) and in Niger (16 %) (Breakwell et al., 2017; Falade et al., 2022) could have contributed for the lower risk of HCC in Ethiopia. Simultaneous human exposure to hepatitis B virus and aflatoxin is reported to increase the oxidative stress in the population contributing to higher HCC risk (Liu et al., 2008). Although Hepatitis C infection is also positively related to HCC risk, with the risk getting worse when hepatitis C and hepatitis B infections co-exist (Okeke et al., 2020), a quantitative relationship between aflatoxin exposure and hepatitis C infection has not been established (Liu and Wu, 2010). In Ethiopia, a total of 69,2000 Hepatitis C infection cases were reported for all ages in 2022 (WHO, 2024).

Although the concentrations of aflatoxin in about 99.2 % of samples were below the FAO/WHO (2024) regulatory limits of 10 ng/g for aflatoxin in unprocessed cereal grains, and process factors were applied for possible reduction of aflatoxins during *injera* processing, the estimated MOE results showed priority for risk management. The estimated median MOE value estimated for the median intake and median body weight in ANRS without considering the reduction factors for aflatoxin concentration (mean = 0.1321 ng/g) was 656, which is much lower than the simulated results estimated considering the process factors as given in Fig. 2. Similar results where aflatoxin concentrations in foods that were below the EU regulatory limits leading to MOE values below 10000 were also reported in Europe (Udovicki et al., 2019) and in Mexico (Sandoval et al., 2019). Indeed, contamination levels in foods below the maximum regulatory limits may not always protect consumers health (Nacim et al., 2017). The simulated DALY results in the ANRS and at national level (Fig. 3) seem to be overestimating the aflatoxin disease burden. That is because for the DALY calculation (Eq. (5)), we used the total number of DALY cases for all age groups since the Global Cancer Observatory (GCO) report (231-ethiopia-fact-sheet.pdf) doesn't provide the data for each age category. Thus, we assumed all liver cancer cases and related DALYs occur on people older than 14 years of age (adults). Although the DALY data available in the Global Disease Burden report (ghe2021_daly_bycountry_2021.xlsx) provides DALY data by different age groups, we didn't use these data because WHO mentioned that the death registration data for Ethiopia are unusable due to quality issues. However, it is important to note that our DALY calculation only considered mortality and not morbidity (EQ (5)). This means that our DALY estimates would underestimate the actual disease burden. Nevertheless, the total DALY due to aflatoxin exposure in Africa ranges from 50 to 400/one million persons/year (Gibb et al., 2015).

For the 97.5 % of sorghum *injera* consumption in the ANRS, the estimated DALY was about 0.05/million persons (Supplementary Table 5). Besides sorghum, other food crops grown in our study sites, such as *teff* and chickpea, are also susceptible to mycotoxin contamination (Alemayehu et al., 2020; Geremew et al., 2018). Consequently, the total exposure to fumonisin and aflatoxin, and the resulting disease burden, could be higher than estimated from sorghum consumption alone. Therefore, future studies need to consider the aflatoxin and fumonisin exposure from all food sources. To further reduce the aflatoxin exposure in the ANRS, interventions on sorghum intake are more interesting than on aflatoxin occurrence (Fig. 4). Provided that aflatoxin exposure is virtually through food intake (Gibb et al., 2015), diversification of food intake, i.e. reducing the daily sorghum intake by partially replacing the sorghum that is used for *injera* preparation with other alternative crops that are less susceptible to mycotoxin contamination, and/or replacing part of the *injera* meal with other safer and healthier alternative foods would be helpful. However, this option is not easy to achieve since finding an alternative grain locally that is less vulnerable to mycotoxin contamination seems difficult. Since sorghum is a staple food, reducing its consumption may be difficult or inappropriate for the local population. A more effective strategy would be to develop and implement a code of practice to mitigate aflatoxin contamination in the local food supply chain, rather than reducing sorghum consumption.

Compared to the estimated aflatoxin exposure and risk in the ANRS, the estimated aflatoxin exposure and risk at the national level were much higher (Supplementary Table 5; Figs. 1–3). These variations are

due to higher input values used for the national-level calculations, namely aflatoxin concentration, sorghum intake, and the proportion of hepatitis B surface antigen-positive individuals, than at the ANRS level (Eq (2), Eq (4), Eq (5)). An increase in body weight would lead to decreased exposure and risk estimates (Eq (2)); however, the body weight values used at the national level and in the ANRS were similar, as evidenced by the mean body weight of 53 kg nationally and 52 kg in the ANRS. This indicates that body weight contributes very little to the variation in exposure and risk estimates. Despite sorghum intake contributed to aflatoxin exposure more than aflatoxin concentration (Fig. 4), sorghum intake levels are similar both in the ANRS and at national level (Supplementary Table 3). This would imply that the higher aflatoxin concentration in sorghum used to estimate the aflatoxin exposure at national level (93.31 ng/g), which is far higher (about 250 %) than the mean aflatoxin concentration in the ANRS (0.37 ± 2.29 ng/g) (Table 1) contributed to the high aflatoxin exposure and disease burden at national level. It is important to note that for the mycotoxin concentration at national level, we assumed a worst-case scenario in which the reported mean values for the individual aflatoxins (AFB1, AFB2, AFG1 and AFG2) were present in the same samples. The concentrations were then added together to calculate the total aflatoxin concentration (Table 1). This could lead to an overestimation of aflatoxin exposure and the resulting disease burden at a national level. For lifetime risk estimation, we assumed that individuals' EDI remains constant throughout their lifetime. Previous biomarker-based studies in Ethiopia indicated unsafe levels of aflatoxin exposure (Ayele et al., 2022; Boshe et al., 2020; Tessema et al., 2021). Besides intervention on sorghum intake, intervention on reducing aflatoxin contamination is also important.

The intervention would be applied through training consumers to create awareness about safer and healthier alternatives to sorghum *injera*. Intervention on hepatitis B virus infection would also be important. According to FAO/WHO (2017); FAO/WHO, 2017, the probability of incidence of HCC is 30 times lower in persons that don't have hepatitis B infection story (HBsAg- surface antigen) than in persons with hepatitis infection (HBsAg + surface antigen).

Although sorghum is the most widely consumed food in our study sites (Supplementary Table 1), other grains, such as maize, wheat, and teff, are also main staples in other parts of the country, depending on agroecological conditions that allow for the growth of these grains, cultural food consumption practices, etc. Therefore, aflatoxin exposure results at the national level may over- or underestimate actual exposure levels, depending on the typical staple food crop in each area. For example, teff is the main staple food crop in the highlands of northwest Ethiopia, and sorghum is consumed to a limited extent. Therefore, the aflatoxin exposure assessment results presented in this study may not accurately reflect the actual risk in this region of Ethiopia, as teff, rather than sorghum, may be the primary source of aflatoxin exposure. In addition, although the results of a lifetime aflatoxin exposure assessment provided insight into the extent of aflatoxin risk with lifetime exposure, this estimation may not be realistic. This is because we assumed, for the lifetime exposure assessment, that individuals could be exposed to the same level of aflatoxin throughout their life. However, this assumption is not true since the variables used to estimate risk may change over time. For example, aflatoxin concentration levels may change due to changes in agricultural practices or climate, while sorghum intake levels may change due to public dietary shifts. Therefore, future research should consider a lifespan of 5 or 10 years, during which time changes are presumed minimal.

5. Conclusions and recommendation

The results in this research provided insights on the fumonisin and aflatoxin exposure from sorghum consumption in the ANRS and at national level in Ethiopia. The related fumonisin exposure does not seem to pose a public health concern in either the ANRS or at national level. On the other hand, aflatoxin exposure is a priority for risk management. Despite aflatoxin exposure showed the presence of public health concern, the corresponding DALY estimates were low in the ANRS. Health concerns have been related mainly to sorghum intake. Therefore, dietary intervention at consumers' level is recommended to reduce aflatoxin exposure. In addition, it would be helpful to implement integrated preventive strategies along the sorghum value chain, covering agricultural production, storage, and handling.

CRediT authorship contribution statement

J.A. Sadik: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **N. Fentahun:** Writing – review & editing, Supervision, Methodology. **I.D. Brouwer:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **M. Tessema:** Supervision, Methodology. **H.J.van der Fels-Klerx:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Ethical declaration

Ethical approval for the interview was obtained from the Bahir Dar University Institutional Review Board (Protocol number 12/IRB/23). Interview data was collected after obtaining the Ethical approval letter, and Written Informed Consent was received before the interview.

Subject: funding body

This is to confirm that this research was funded by Wageningen University & Research Graduate Schools Sandwich PhD programme; [grant number - 2100963900].

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.yrtph.2025.105966.

Data availability

Data will be made available on request.

References

Abhay, K.P., Samota, M.K., Kumar, A., Silva, A.S., Dubey, N.K., 2023. Fungal mycotoxins in food commodities: present status and future concerns. Front. Sustain. Food Syst. 7, 1162595. https://doi.org/10.3389/fsufs.2023.1162595.

Adebo, O.A., Kayitesi, E., Njobeh, P.B., 2019. Reduction of mycotoxins during fermentation of whole grain sorghum to whole grain ting (a southern African food). Toxins 11 (3). https://doi.org/10.3390/toxins11030180.

Alemayehu, S., Abay, F., Ayimut, K.M., Assefa, D., Chala, A., Mahroof, R., Harvey, J., Subramanyam, B., 2020. Evaluating different hermetic storage technologies to arrest mold growth, prevent mycotoxin accumulation and preserve germination quality of stored chickpea in Ethiopia. J. Stored Prod. Res. 85. https://doi.org/10.1016/j.jspr.2019.101526.

Andrade, P.D., Dias, J.V., Souza, D.M., Brito, A.P., van Donkersgoed, G., Pizzutti, I.R., Caldas, E.D., 2020. Mycotoxins in cereals and cereal-based products: incidence and probabilistic dietary risk assessment for the Brazilian population. Food Chem. Toxicol. 143, 111572. https://doi.org/10.1016/j.fct.2020.111572.

Atnkut, B., Nigussie, A., Berza, B., Mikru, A., Zhao, B., Astatkie, T., 2025. Mycotoxins contaminations in Ethiopian food: impacts, challenges, and mitigation strategies. Food Control 171. https://doi.org/10.1016/j.foodcont.2024.111066.

Ayalew, A., Fehrmann, H., Lepschy, J., Beck, R., Abate, D., 2006. Natural occurrence of mycotoxins in staple cereals from Ethiopia. Mycopathologia 162 (1), 57–63. https://doi.org/10.1007/s11046-006-0027-8.

Ayele, M., Haile, D., Alonso, S., Sime, H., Abera, A., Balcha, K.H., Roba, K.T., Guma, G.T., Endris, B.S., 2022. Aflatoxin exposure among children of age 12–59 months in Butajira district, south-central Ethiopia: a community based cross-sectional study. BMC Pediatr. 22, 326. https://doi.org/10.1186/s12887-022-03389-w.

Baye, K., Mouquet-Rivier, C., Icard-Vernière, C., Picq, C., Guyot, J.P., 2013. Changes in mineral absorption inhibitors consequent to fermentation of Ethiopian injera: implications for predicted iron bioavailability and bioaccessibility. Int. J. Food Sci. Technol. 49 (1), 174–180. https://doi.org/10.1111/ijfs.12295.

Beyene, A.A., Woldegiorgis, A.Z., Adish, A.A., Saeger, S.D., Tolossa, A.L., 2016. Assessment of mothers' knowledge and practice towards aflatoxin contamination in complementary foods in Ethiopia: from pre-harvest to household. World Mycotoxin J. 9 (4), 535–544. https://doi.org/10.3920/WMJ2016.2088.

Bikila, G.M., Tola, Y.B., Kuyu, C.G., 2024. Standardization of teff (Eragrostis teff) injera making process conditions for better physicochemical and sensory quality. Food Sci. Nutr. 12 (5), 3417–3432. https://doi.org/10.1002/fsn3.4006.

Boshe, B., Gebremedhin, S., Alemayehu, F., Eshete, M., Taye, M., Stoecker, B.J., 2020. Aflatoxin exposure among lactating women in southern Ethiopia. Food Sci. Nutr. 8, 6738–6745. https://doi.org/10.1002/fsn3.1968.

Braun, M.S., Wink, M., 2018. Exposure, occurrence, and chemistry of fumonisins and their cryptic derivatives. Compr. Rev. Food Sci. Food Saf. 17 (3), 769–791. https://doi.org/10.1111/1541-4337.12334.

Breakwell, L., Tevi-Benissan, C., Childs, L., Mihigo, R., Tohme, R., 2017. The status of hepatitis B control in the African region. Pan. Afr. Med. J. 27 (Suppl. 3), 17. https://doi.org/10.11604/pamj.supp.2017.27.3.11981.

Bucci, T.J., Howard, P.C., Tolleson, W.H., Laborde, J.B., Hansen, D.K., 1998. Renal effects of fumonisin mycotoxins in animals. Toxicol. Pathol. 26 (1), 160–164.

Chala, A., Taye, W., Ayalew, A., Krska, R., Sulyok, M., Logrieco, A., 2014. Multimycotoxin analysis of sorghum (Sorghum bicolor L. Moench) and finger millet (Eleusine coracana L. Garten) from Ethiopia. Food Control 45, 29e35. https://doi.org/10.1016/j.foodcont.2014.04.018.

CSA, 2020. Agricultural Sample Survey Report on Area, Production and Farm Management Practice of Belg Season Crops for Private Peasant Holdings, 578. Addis Abeba.

Derese, S.A., Shimelis, H., Laing, M., Mengistu, F., 2018. The impact of drought on sorghum production, and farmer's varietal and trait preferences, in the north eastern Ethiopia: implications for breeding. ACTA Agriculture Scandinavica, Section B - Soil & Plant Science 68 (5), 424–436. https://doi.org/10.1080/09064710.2017.1418018.

EFSA, 2010. Management of left-censored data in dietary exposure assessment of chemical substances, 8(3), 1557. https://doi.org/10.2903/j.efsa.2010.155710.2903/j.efsa.2010.1557. . Available.

EFSA, 2018. Risks for animal health related to the presence of fumonisins, their modified forms and hidden forms in feed. EFSA J. 160 (5), e05242. https://doi.org/10.2903/j.efsa.2018.5242.

EFSA, 2020. Risk assessment of aflatoxins in food. EFSA J. 18 (3), 6040. https://doi.org/10.2903/j.efsa.2020.6040.

EPHI, 2025. Ethiopia Food and Nutrition Strategy Baseline Survey 2021–2022. Addis Ababa.

Falade, T.D.O., Neya, A., Bonkoungou, S., Dagno, K., Basso, A., Senghor, A.L., Atehnkeng, J., Ortega-Beltran, A., Bandyopadhyay, R., 2022. Aflatoxin contamination of maize, groundnut, and sorghum grown in Burkina Faso, Mali, and niger and aflatoxin exposure assessment. Toxins 14 (10). https://doi.org/10.3390/toxins14100700.

Fandohan, P., Zoumenou, D., Hounhouigan, D.J., Marasas, W.F.O., Wingfield, M.J., Hell, K., 2005. Fate of aflatoxins and fumonisins during the processing of maize into food products in Benin. Int. J. Food Microbiol. 98, 249–259. https://doi.org/10.1016/j.ijfoodmicro.2004.07.007.

FAO/WHO, 2014. Joint FAO and WHO food standards programme codex committee on contaminants in food, Eighth Session. Discussion paper on aflatoxin levels in cereals, CX/CF 14/8/15.

FAO/WHO, 2017. Evaluation of certain contaminants in food. In Eighty-third report of the Joint FAO/WHO Expert Committee on Food Additives (JECFA/83/SC). WHO Technical Report Series 1002, Geneva, Switzerland.

FAO/WHO, 2024. General standard for contaminants and toxins in foods and feed. Revised in forty-seventh session of the codex alimentarius commission in November 2024. CXS 193–1995.

Fox, G., Nugusu, Y., Nida, H., Tedessa, T., McLean, G., Jordan, D., 2020. Evaluation of variation in Ethiopian sorghum injera quality with new imaging techniques. Cereal Chem. 97, 362–372. https://doi.org/10.1002/cche.10252.

GEMS/Food-EURO, 1995. Reliable evaluation of low-level contamination of food. In: Report on a Workshop in the Frame of GEMS/Food-EURO. Kulmbach, Germany.

Geremew, T., Haesaert, G., Abate, D., Audenaert, K., 2018. An HPLC-FLD method to measure ochratoxin A in teff (Eragrostis tef) and wheat (Triticum spp.) destined for the local Ethiopian market. World Mycotoxin J. 11 (3), 359–368. https://doi.org/10.3920/wmj2017.2175.

Gibb, Devleesschauwer, B., Bolger, P.M., Wu, F., Ezendam, J., Cliff, J., Zeilmaker, M., Verger, P., Pitt, J., Baines, J., Adegoke, G., Afshari, R., Liu, Y., Bokkers, B., van Loveren, H., Mengelers, M., Brandon, E., Havelaar, A.H., Bellinger, D., 2015. World health organization estimates of the global and regional disease burden of four foodborne chemical toxins, 2010: a data synthesis. F1000Res 4, 1393. https://doi.org/10.12688/f1000research.7340.1.

Herojeet, R., Dewangan, R.K., Naik, P.K., Verma, J.R., 2023. Probabilistic modelling is superior to deterministic approaches in the human health risk assessment: an example from a tribal stretch in central India. Sci. Rep. 13 (1), 19351. https://doi.org/10.1038/s41598-023-45622-1.

Liang, J., Ning, M., Guan, S., Fang, L., Chen, X., Dong, Z., Fan, L., 2021. Risk assessment of multiple mycotoxin exposure for consumers of chestnuts in Shandong Province markets in China. Food Addit. Contam. 38 (12), 2137–2150. https://doi.org/10.1080/19440049.2021.1970240.

Liu, Y., Wu, F., 2010. Global burden of aflatoxin-induced hepatocellular carcinoma: a risk assessment. Environ. Health Perspect. 118 (6), 818–824. https://doi.org/10.1289/ehp.0901388.

Liu, Z.M., Li, L.Q., Peng, M.H., Liu, T.W., Qin, Z., Guo, Y., Xiao, K.Y., Ye, X.P., Mo, X.S., Qin, X., Li, S., Yan, L.N., Shen, H.M., Wang, L., Wang, Q., Wang, K.B., Liang, R.X., Wei, Z.L., Ong, C.N., Peng, T., 2008. Hepatitis B virus infection contributes to oxidative stress in a population exposed to aflatoxin B1 and high-risk for hepatocellular carcinoma. Cancer Lett. 263 (2), 212–222. https://doi.org/10.1016/j.canlet.2008.01.006.

Marasas, W.F., Riley, R.T., Hendricks, K.A., Stevens, V.L., Sadler, T.W., Gelineau-van Waes, J., Missmer, S.A., Cabrera, J., Torres, O., Gelderblom, W.C., Allegood, J., Martinez, C., Maddox, J., Miller, J.D., Starr, L., Sullards, M.C., Roman, A.V., Voss, K. A., Wang, E., Merrill Jr., A.H., 2004. Fumonisins disrupt sphingolipid metabolism, folate transport, and neural tube development in embryo culture and in vivo: a potential risk factor for human neural tube defects among populations consuming fumonisin-contaminated maize. J. Nutr. 134 (4), 711–716. https://doi.org/10.1093/jn/134.4.711.

Matumba, L., Kimanya, M., Chunga-Sambo, W., Munthali, M., Ayalew, A., 2019. Probabilistic dietary based estimation of the burden of aflatoxin-induced hepatocellular carcinoma among adult Malawians. World Mycotoxin J. 12 (4), 409–419. https://doi.org/10.3920/WMJ2018.2346.

Mesfin, A., Lachat, C., Gebreyesus, S.H., Roro, M., Tesfamariam, K., Belachew, T., Boevre, M.D., Saeger, S.D., 2023. Mycotoxins exposure of lactating women and its relationship with dietary and Pre/post-harvest practices in rural Ethiopia. Toxins 15, 285. https://doi.org/10.3390/toxins15040285.

Mihalache, A.O., Torrijos, R., Dall'Asta, C., 2024. Occurrence of mycotoxins in meat alternatives: dietary exposure, potential health risks, and burden of disease. Environ. Int. 185, 108537. https://doi.org/10.1016/j.envint.2024.108537.

MOA, 2020. Crop Variety Register, Plant Variety Release, Protection and Seed Quality Control Directorate, Ministry of Agriculture, Federal Democratic Republic of Ethiopia, Addis Ababa.

MOH, 2021. National Strategic Plan for Prevention and Control of Viral Hepatiti in Ethiopia, 2021-2025. Addis Ababa, Ethiopia.

Mohammed, A., Bekeko, Z., Yusufe, M., Sulyok, M., Krska, R., 2022. Fungal species and multi-mycotoxin associated with post-harvest sorghum (Sorghum bicolor (L.) moench) grain in eastern Ethiopia. Toxins 14, 473. https://doi.org/10.3390/toxins14070473.

Mulisa, G., Pero-Gascon, R., McCormack, V., Bisanz, J.E., Talukdar, F.R., Abebe, T., De Boevre, M., De Saeger, S., 2024. Multiple mycotoxin exposure assessment through human biomonitoring in an esophageal cancer case-control study in the Arsi-Bale districts of Oromia region of Ethiopia. Int. J. Hyg Environ. Health 263, 114466. https://doi.org/10.1016/j.ijheh.2024.114466.

Nacim, N.M., Hammoudi, A., Radjef, M.S., Hamza, O., Perito, M.A., 2017. How do food safety regulations influence market price? A theoretical analysis. Br. Food J. 119 (8), 1687–1704. https://doi.org/10.1108/bfj-12-2016-0594.

Nikiéma, P.N., Worrillow, L., Traoré, A.S., Wild, C.P., Turner, P.C., 2004. Fumonisin contamination of maize in Burkina Faso, West Africa. Food Addit. Contam. 21 (9), 865–870. https://doi.org/10.1080/0265-2030400004242.

Okechukwu, V.O., Adelusi, O.A., Kappo, A.P., Njobeh, P.B., Mamo, M.A., 2024. Aflatoxins: occurrence, biosynthesis, mechanism of action and effects, conventional/emerging detection techniques. Food Chem. 436, 137775. https://doi.org/10.1016/j.foodchem.2023.137775.

Okeke, E., Davwar, P.M., Roberts, L., Sartorius, K., Spearman, W., Malu, A., Duguru, M., 2020. Epidemiology of liver cancer in Africa: current and future trends. Semin. Liver Dis. 40 (2), 111–123. https://doi.org/10.1055/s-0039-3399566.

Ren, Y., Zhang, Y., Lai, S., Han, Z., Wu, Y., 2011. Simultaneous determination of fumonisins B1, B2 and B3 contaminants in maize by ultra high-performance liquid chromatography tandem mass spectrometry. Anal. Chim. Acta 692 (1–2), 138–145. https://doi.org/10.1016/j.aca.2011.03.005.

Sadik, J.A., Righetti, L., Fentahun, N., Brouwer, I.D., Tessema, M., Abera, M., van der Fels-Klerx, H.J., 2025. Storage management practices and mycotoxin contamination of sorghum (Sorghum bicolor) in northwest Ethiopia. J. Stored Prod. Res. 111. https://doi.org/10.1016/j.jspr.2024.102535.

Sandoval, I.G., Wesseling, Sebastiaan, Rietjens, I.M.C.M., 2019. Aflatoxin B1 in nixtamalized maize in Mexico; occurrence and accompanying risk assessment. Toxicol. Rep. 6, 1135–1142. https://doi.org/10.1016/j.toxrep.2019.10.008.

Ssepuuya, G., Ediage, C.V.P.E.N., Tritscher, C.M.A., Verger, P., Kenny, M., Bessy, C., Saeger, S.D., 2018. Mycotoxin contamination of sorghum and its contribution to human dietary exposure in four sub-saharan countries. Food Addit. Contam. 35 (7), 1384–1393. https://doi.org/10.1080/19440049.2018.1461253.

Taye, W., Ayalew, A., Challa, A., Dejene, M., 2016. Aflatoxin B1 and total fumonisin contamination and their producing fungi in fresh and stored sorghum grain in East Hararghe, Ethiopia. In: Food Additives & Contaminants. Part B Surveillance, pp. 1939–3229. https://doi.org/10.1080/19393210.2016.1184190.

Taye, W., Ayalew, A., Dejene, M., Chala, A., 2018. Fungal invasion and mycotoxin contamination of stored sorghum grain as influenced by threshing methods. Int. J. Pest Manag. 64 (1), 66–76. https://doi.org/10.1080/09670874.2017.1327681.

Tessema, M., Groote, H.D., Brouwer, I.D., Boevre, M.D., Corominas, A.V., Stoecker, B.J., Feskens, E.J., Belachew, T., Karakitsou, A., Gunaratna, N.S., 2021. Exposure to aflatoxins and fumonisins and linear growth of children in rural Ethiopia: a

longitudinal study. Public Health Nutr. https://doi.org/10.1017/S1368980021000422.

Udovicki, B., Djekic, I., Kljusuric, J.G., Papageorgiou, M., Skendi, A., Djugum, J., Rajkovic, A., 2019. Exposure assessment and risk characterization of aflatoxins intake through consumption of maize products in the adult populations of Serbia, Croatia and Greece. Food Addit. Contam. 36 (6), 940–951. https://doi.org/10.1080/19440049.2019.1600748.

WHO, 2024. Global Hepatitis Report 2024: Action for Access in low- and middle-income Countries. Geneva, Switzerland.

Wokorach, G., Landschoot, S., Anena, J., Audenaert, K., Echodu, R., Haesaert, G., 2021. Mycotoxin profile of staple grains in northern Uganda: understanding the level of human exposure and potential risks. Food Control 122 (122), 107813. https://doi.org/10.1016/j.foodcont.2020.107813.

Wu, F., Groopman, J.D., Pestka, J.J., 2014. Public health impacts of foodborne mycotoxins. Annu. Rev. Food Sci. Technol. (5), 351–372. https://doi.org/10.1146/annurev-food-030713-092431.

Yetneberk, S., Rooney, L.W., Taylor, J.R.N., 2005. Improving the quality of sorghum injera by decortication and compositing with tef. J. Sci. Food Agric. 85 (8), 1252–1258. https://doi.org/10.1002/jsfa.2103.