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Mycotoxin contamination in plant-based beverages and meat alternatives: A survey of the UK market

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ABSTRACT

The study aimed to investigate the natural occurrence and co-occurrence of nineteen mycotoxins in 212 plant-based products collected from several retailers in the UK, including plant-based meat alternatives (PBMAs) ($n = 92$) and plant-based beverages (PBBs) ($n = 120$), using liquid chromatography coupled to mass spectrometry in tandem (LC-MS/MS). Mycotoxins included in the analysis were aflatoxins (AFB_1, AFB_2, AFG_1, AFG_2), ochratoxin A (OTA), zearalenone (ZEN), fumonisins (FB_1, FB_2), deoxynivalenol (DON), HT-2/T-2, enniatins (ENNB, $ENNB_1$, ENNA, $ENNA_1$), beauvericin (BEA), alternariol (AOH), alternariol monomethyl ether (AME), and tentoxin (TEN). A high prevalence of emerging *Fusarium* toxins such as ENNA (93.5 %), ENNA1 (93.5 %), and BEA (98.9 %), and the *Alternaria* toxins AOH (75.0 %), AME (85.9 %), and TEN (77.2 %), was found in the PBMAs. Similarly, BEA, ENNB, and ENNA were frequently found in the PBBs of the study, with prevalence values ranging from 71.9 % to 100 %. In general, all mycotoxins were found in significantly higher concentrations in the PBMAs compared to the PBBs. The high co-occurrence observed across the samples suggests that food business operators should prioritize the management of mycotoxins in plant-based products as an integral part of their food safety systems. Moreover, further monitoring studies should be conducted to assess the potential risks associated with the consumption of plant-based products, considering the current dietary habits of the population.

1. Introduction

The growing concerns about environmental impact and animal welfare implications of the current food systems (Duluins & Baret, 2024; Prag & Henriksen, 2020; Smetana et al., 2023) have accelerated the adoption of plant-based diets among consumers, such as vegetarianism, veganism, and flexitarianism, as a sustainable alternative to animal-based diets. This transition has driven the fast development and commercialization of plant-based meat alternatives (PBMAs) and plant-based beverages (PBBs) that aim to satisfy consumers' demands (Ahmad et al., 2022).

The European market for plant-based products has experienced unprecedented growth in recent years. In contrast the UK experienced a modest decline of −2.8 % between 2022 and 2023, despite still achieving £942 million in sales. This contraction is tied to the UK's broader cost-of-living crisis, oversaturation, consumer preference for better taste and association of plant-based alternatives with ultra-processed foods (gfieurope.org, 2024a).

The largest plant-based product categories are by far represented by PBMAs and PBBs, accounting for 40 % and 43 % of the overall plant-based sales value in the UK and representing £373 million and £404 million in sales, respectively (data from 2023) (gfieurope.org, 2024b).

While the environmental and nutritional benefits of an increased plant-based product consumption are well-established (Medici et al., 2023; Gibbs & Cappuccio, 2022), gaps are still present in their safety assessment, and more specifically regarding the occurrence of potential unregulated contaminants. Among them, mycotoxins have often been reported as of particular concern due to their widespread occurrence in crops (Mihalache et al., 2022; Schryvers et al., 2025). Mycotoxins are fungal secondary metabolites produced mainly by the *Aspergillus*, *Penicillium*, *Fusarium*, and *Alternaria* genera. They possess a wide range of toxicological effects, including hepatotoxicity, nephrotoxicity,

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estrogenicity, immunotoxicity, and carcinogenicity (Milićević et al., 2010). Among them, aflatoxins (AFs) of group B (AFB_1, AFB_2) and G (AFG_1, AFG_2) are of special concern since they are classified as Group 1 carcinogens according to the International Agency for Research on Cancer (IARC) due to their mutagenic and carcinogenic potential (IARC, 2019). Other mycotoxins, such as ochratoxin A (OTA) and fumonisins (FBs), are classified as probably carcinogenic to humans (group 2A) by IARC based on current evidence (Ostry et al., 2017). Mycotoxins can be synthesized throughout the food chain, and once produced, they are highly stable and complex to remove entirely using conventional food processing techniques (Bullerman & Bianchini, 2007; Karlovsky et al., 2016) A recent study of soy-based burgers prototypes showed the presence of tentoxin, at early stages of product development (e.g., soy protein isolate) (Cutroneo et al., 2025) Therefore, if the raw materials used in the manufacture of PBMAs and PBBs are contaminated with mycotoxins, it is highly likely that the contamination will be transferred to the final product. Given the increased consumption, an appropriate risk assessment is needed to consider the change in dietary pattern among the target population (Alae-Carew et al., 2022). With only a few studies exploring the prevalence of mycotoxins in PBMAs and PBBs, a clearer picture of mycotoxin occurrence in plant-based foods is still lacking (Cutroneo et al., 2025a; Mihalache et al., 2024; Pavlenko et al., 2024; Rodríguez-Cañás et al., 2023; Torrijos et al., 2025). While major mycotoxins are currently regulated at the global level in certain food categories through the Codex Alimentarius Commission General Standard for Contaminants and Toxins in Food and Feed (CXS 193-1995) (Codex Alimentarius Commission, 1995), and at the European level through the Commission Regulation (EC) 2023/915, no specific legislation or monitoring plans have been established for PBMAs and PBBs. To the best of our knowledge, the UK market is still unexplored in terms of mycotoxin prevalence in PBMAs and PBBs. Consequently, there is a clear need to expand the information on mycotoxin contamination in these commodities to provide high-quality data that allow a proper risk assessment. The aim of the study was to develop a thorough assessment of the prevalence of nineteen mycotoxins in PBMAs ($n = 92$) and PBBs ($n = 120$) from the UK market, applying a previous validated salt-assisted liquid-liquid extraction (SALLE) followed by ultra-high performance liquid chromatography coupled to mass spectrometry in tandem (UHPLC-MS/MS) (Mihalache et al., 2024; Torrijos et al., 2025). The analytes included were the regulated mycotoxins AFB_1, AFB_2, AFG_1, AFG_2, OTA, FB_1, FB_2, zearalenone (ZEN), deoxynivalenol (DON), HT-2, T-2, the emerging mycotoxins from the *Fusarium* genera enniatin B (ENNB), enniatin B_1 (ENB_1), enniatin A (ENNA), enniatin A_1 ($ENNA_1$), beauvericin (BEA), and the *Alternaria* mycotoxins alternariol (AOH), alternariol monomethyl ether (AME), and tentoxin (TEN).

2. Material and methods

2.1. Chemicals and reagents

LC/MS-grade methanol (MeOH), acetonitrile (MeCN), ultrapure water, formic acid (FA), and acetic acid were obtained from VWR Chemicals (VWR International, Milan, Italy). The salts ammonium acetate and anhydrous magnesium sulfate ($MgSO_4$) were purchased from Sigma-Aldrich (Sigma-Aldrich, Milan, Italy).

Commercially available analytical standards of aflatoxin B_1 (AFB_1), aflatoxin B_2 (AFB_2), aflatoxin G_1 (AFG_1), and aflatoxin G_2 (AFG_2) were provided by Fermentek.Ltsd (Jerusalem, Israel). Ochratoxin A (OTA), zearalenone (ZEN), HT-2, T-2, and deoxynivalenol (DON) and the emerging mycotoxins alternariol (AOH), alternariol monomethyl ether (AME), tentoxin (TEN), enniatin B (ENNB), enniatin B_1 ($ENNB_1$), enniatin A (ENNA), enniatin A_1 ($ENNA_1$), and beauvericin (BEA) were purchased from Romer Labs (Tulln, Austria). A mixture of fumonisin (FB_1) and fumonisin B2 (FB_2) in MeOH:H_2O (50:50, v/v), was also obtained from Romer Labs (Tulln, Austria). Dried powders of mycotoxins were dissolved in the appropriate solvent according to manufacturer instructions. Working solutions of 1 μg L^{-1} were prepared, combining all analytes in MeCN, except FB_1 and FB_2, which were prepared separately at 1 μg L^{-1} in MeOH:H_2O (50:50, v/v). Working solutions were then further diluted to obtain matrix-matched calibration curves for quantification. The working solutions were stored at −20 °C and prepared freshly every month.

2.2. Sample collection and storage

A total of 92 samples of commercially available PBMAs and 120 samples of PBBs were purchased in Bedfordshire, United Kingdom, between January and February 2024. Products were obtained from the top five UK retailers, which were chosen because they collectively represent most of the national plant-based food market. The sampling followed a convenience-based random selection, with the aim of covering a broad range of product types and brands available to UK consumers at the time of purchase. Some of the PBMAs were classified according to their primary ingredient used in the formulation as cereal-based meat alternatives (CBMA) ($n = 10$) or legume-based meat alternatives (LBMA) ($n = 30$). However, due to the complexity of the product formulation found in the meat analogs, combinations of ingredients were also considered in the classification, and two additional groups were added: legumes and cereals-based meat alternatives (LCBMA) ($n = 27$) and legumes and vegetables-based meat alternatives (LVBMA) ($n = 25$). The PBMAs purchased in the study and their main ingredients are described in Supplementary Material 1. The PBBs were classified according to the following ingredients: oat-based (OBB, $n = 57$), almond/nuts-based (ABB, $n = 32$), and soy-based (SBB, $n = 31$). Classification of PBBs was based primarily on the main ingredient used in their manufacture, according to the percentage composition, and, in some cases, on the product labeling intended for consumers. As presented in Supplementary Material 2, the classification of some PBBs was sometimes challenging because several products contained multiple plant ingredients in varying proportions. In these cases, the ingredient present in the highest proportion was used to assign the product category. In some ABBs, rice was also present as an ingredient, although it was occasionally listed with unspecified percentages. Since the number of rice-based beverages identified on the UK market was insufficient to establish a separate representative group, these samples were classified as ABBs, in accordance with their labeling intended for consumers.

The entire PBMAs samples (net weights ranging from 60 to 500 g) were ground and homogenized using a food grinder (Osterizer Blender, Sunbeam Oster Household Products, Florida, USA). Then, a representative portion (approximately 50 g) was obtained by taking multiple small portions from random positions across the homogenized sample. Finally, the sample was transferred into a Falcon Tube and stored in a freezer (−20 °C) until analysis. The PBBs were preserved in their original confection and refrigerated (4 °C). In both cases, the products were analyzed before the expiration date indicated by the manufacturer.

2.3. Mycotoxin extraction in plant-based meat alternatives (PBMAs)

The mycotoxin extraction from PBMAs was done following the methodology described by Mihalache et al. (2024). A representative sample of each PBMA (1.000g ± 0.005g) was extracted by adding 5 mL of acidified water 0.5 % FA (v/v) and 1 g of anhydrous $MgSO_4$ in a 15-mL Falcon tube. Samples were vortexed for 1 min, then 3 mL of MeCN were added and vortexed again for 5 min. Next, samples were centrifuged for 10 min at 10,000 rpm at 4 °C. 1 mL of the organic phase was transferred in glass vials and dried with N_2. Samples were reconstituted in 200 μL of MeOH/H_2O (75/25, v/v), vortexed, and stored at −20 °C until UHPLC-MS analysis.

2.4. Mycotoxin extraction in plant-based beverages (PBBs)

Mycotoxin extraction in PBBs was performed following the protocol

established by Torrijos et al. (2025). In brief, 5 mL of PBB was placed in a 15 mL Falcon tube, and 3 mL of MeCN acidified with 1.5 % FA (v/v) was added and vortexed 1 min. Then, 2 g of $MgSO_4$ was added and vortexed again for 1 min. The mixture obtained was centrifuged for 5 min at 10, 000 rpm at 4 °C, and then, 1 mL of the organic up-layer phase was recovered and dried under N_2 flow. The dried extracts were resuspended in 200 μL of MeOH/H_2O (75/25, v/v), vortexed, and injected into the ultra-high performance liquid chromatography (UHPLC) system.

2.5. Instrumentation and conditions

The analysis of mycotoxins was performed in a UHPLC Dionex Ultimate 3000 coupled to a triple quadrupole mass spectrometer (TSQ Vantage; Thermo Fisher Scientific Inc., San Jose, CA, USA) and equipped with an electrospray ionization interface (ESI). An XSelect® HSS T3 column (2.1 × 150 mm, 2.5 μm) (Waters, Wexford, Ireland) was used for chromatographic separation. A binary mobile phase consisting of ultrapure water with 0.2 % acetic acid (v/v) and 5 mM of ammonium acetate (solvent A) and MeOH with 0.2 % acetic acid (v/v) (solvent B) was used at a flow rate of 0.4 mL min^{-1}. The following gradient elution was applied: 0 min, 5 % B; 8 min, 90 % B; 12 min, 5 % B, 18 min, 5 %B. Column temperature was kept at 40 °C and the injection volume selected was 3 μL.

The mass spectrometer operated in both positive (ESI^+) and negative (ESI^-) electrospray ionization mode. Instrumental parameters were programmed as follows: spray voltage 3,500V; capillary temperature 270 °C; vaporizer temperature 200 °C; sheath gas (N_2) 50 units; auxiliary gas (N_2) 5 units.

Data acquisition was achieved using multiple-reaction monitoring mode (MRM). For each analyte, two product ions were monitored (Commission Decision (EC) No. 657/2002) (European Commission, 2002). In order to improve sensitivity, four different time segments were established. The optimal MS/MS parameters are described in Supplementary Material 3. The mycotoxin identification in the samples was confirmed by comparing the retention times and MS/MS spectra with those obtained from the respective standards.

Our previous studies validated the UHPLC-MS/MS method for multi-mycotoxin analysis in PBMAs and PBBs, covering the food categories evaluated in this study (Mihalache et al., 2024; Torrijos et al., 2025), in accordance with the SANTE guidelines (SANTE/12089/2016, SANTE/11312/2021), and Commission Regulation 2023/2782/EC. Since a high matrix effect was demonstrated, matrix-matched calibration curves were used for quantification purposes. For this, a blank LBMA was used as a representative matrix for PBMA analysis, whereas a blank OBB, a blank ABB, and a blank SBB were used as representative matrices for PBB analysis. Depending on the matrix and analyte, calibration curves consisting of 6–10 concentration levels were prepared. For PBMAs, the quantification range was generally 0.1–60 μg kg^{-1}, whereas for PBBs, the quantification range was 0.02–10 μg L^{-1}. Solvent and blanks were regularly injected during the analysis. Moreover, for long sequences, the calibration curve was injected every 20 samples to observe potential intensity shifts. An overview of the method's performance, including the limits of detection (LOD) and limits of quantification (LOQ) for PBMAs, OBBs, ABBs, and SBBs is reported in Supplementary Material 4.

2.6. Statistical analysis

Descriptive statistics such as occurrence frequency, mean, median, and range were performed with SPSS 26 (IBM Software Group, Chicago, IL) and Office Excel 2021 (Microsoft Corp., Redmond, Washington, USA). Average and median levels were calculated using two approaches for: a) only samples with quantified levels (<LOQ); b) for total mycotoxin content, values below the LOD and/or LOQ were set to zero. Since the data did not meet the assumption of normality, checked by the Shapiro-Wilk test ($p < 0.05$), the Kruskal–Wallis H test was used to assess significant differences ($p < 0.05$) among mycotoxin levels in the PBMAs and PPBs. We performed pairwise comparisons with Bonferroni corrections to adjust significant values for multiple testing. Comparisons included (i) PBMAs vs. PBBs, and (ii) within-category groups defined by the dominant raw material (e.g., cereal-, legume-, or soy-based PBMAs; oat-, almond-, or soy-based PBBs).

Additionally, data below the limit of detection (LOD) or limit of quantification (LOQ) also known as left-censored data (LCD) were treated using the substitution approach (EFSA, 2010). This approach considers a lower bound (LB) and upper bound (UB) scenario. In the LB the values below LOD and/or LOQ are replaced by zero, while in the UB the values below LOD and/or LOQ are replaced by the value of the LOD and/or LOQ from the method used for the analysis (EFSA, 2010).

3. Results

3.1. Mycotoxin occurrence in plant-based meat alternatives (PBMAs)

The distribution and concentration of nineteen mycotoxins were studied for the first time in PBMAs collected in the UK market. All the products contained at least one of the analytes assessed in the study. The main findings are reported in Tables 1–4 for CBMA, LBMA, LCBMA, and LVBMA, respectively. To check the occurrence values in the lower and upper bound scenarios for PBMAs, please check Supplementary Material 5.

AFs were found in up to 82.6 % of the samples analyzed ($n = 92$), with a higher prevalence (64 %–66.7 %) in legume-based products. The mean quantified contamination level ranged from 0.57 μg kg^{-1} in CBMA to 0.79 μg kg^{-1} in LVBMA.

OTA was detected in more than half of the samples (overall occurrence of 62 %), with mean quantified values ranging between 0.98 μg kg^{-1} (LVBMA) and 1.15 μg kg^{-1} (LCBMA).

Similarly, ZEN was frequently found in the PBMAs, with prevalence levels varying from 50 % in CBMAs to 77.8 % in LCBMAs, and mean quantified contamination values ranging from 1.03 to 1.13 μg kg^{-1}.

When it comes to *Fusarium* mycotoxins, FBs were prevalent across the PBMAs, with prevalence up to 75.0 %. While DON was only found in 3 out of 92 samples, HT-2 and T-2 toxins were frequently detected in cereal-based products, with maximum contamination values of 7.14 μg kg^{-1} and 5.18 μg kg^{-1}, respectively.

Concerning the so-called emerging mycotoxins, a high prevalence was found in all the product categories, although with quantified levels in the low μg kg^{-1} range. BEA was the most prevalent mycotoxin in our study, found in 92/93 products.

Alternaria mycotoxins AOH, AME, and TEN showed an elevated prevalence among the PBMAs, particularly AME, found in 79/92 samples at mean quantified values ranging from 0.38 μg kg^{-1} (CBMA) to 0.58 μg kg^{-1} (LBMA).

A lower prevalence of ENNB and $ENNB_1$ was evidenced in the PBMAs (occurrence 9/92, 9.8 % for ENNB; occurrence 26/92, 28.3 % for $ENNB_1$). Regarding ENNA and $ENNA_1$, the prevalence was higher, with an overall prevalence of 93.5 %.

3.2. Mycotoxin occurrence in plant-based beverages (PBBs)

A total of 120 PBBs, comprising OBBs ($n = 57$), ABBs ($n = 32$), and SBBs ($n = 31$), were studied to offer insight into mycotoxin contamination. All the PBBs included in the survey contained at least one of the mycotoxins monitored. Overall, the mycotoxin distribution varied in the PBBs depending on the main ingredient used in the formulation. Notably, OBBs had the highest number of detected mycotoxins among the beverage categories, followed by SBBs and ABBs. The results, including prevalence and contamination values of OBBs, ABBs, and SBBs, are presented in Tables 5, 6, and 7, respectively. To check the occurrence values in the lower and upper bound scenarios for PBBs, please check Supplementary Material 5.

Table 1
Occurrence, percentage of left-censored data, average, median, and range of contamination values for the quantified mycotoxins (>LOQ) and the average and median values for the total mycotoxins found in the cereal-based meat alternatives (CBMA) ($n = 10$).

Mycotoxin[a]	Occurrence, (%)	% of LCD	Minimum level, μg kg^{-1}	Maximum level, μg kg^{-1}	Average contamination level (quant.) ± STD, μg kg^{-1}	Median contamination level (quant.), μg kg^{-1}	Average contamination level (total)[b] ± STD, μg kg^{-1}	Median contamination level (total)[b], μg kg^{-1}
AFB_1	5 (50.0)	50.0	0.48	0.71	0.57 ± 0.09	0.53	0.29 ± 0.31	0.24
AFB_2	4 (40.0)	60.0	0.55	0.83	0.66 ± 0.13	0.63	0.26 ± 0.35	0
AFG_1	2 (20.0)	80.0	0.75	0.92	0.83 ± 0.12	0.83	0.17 ± 0.35	0
AFG_2	2 (20.0)	80.0	0.51	0.74	0.62 ± 0.16	0.62	0.12 ± 0.27	0
AOH	6 (60.0)	40.0	1.24	6.67	2.92 ± 2.05	2.42	1.75 ± 2.14	1.33
AME	7 (70.0)	30.0	0.34	0.43	0.38 ± 0.04	0.39	0.27 ± 0.18	0.36
TEN	7 (70.0)	30.0	0.58	1.58	1.01 ± 0.34	0.95	0.70 ± 0.56	0.81
FB_1	6 (60.0)	40.0	1.24	4.49	2.05 ± 0.122	1.68	1.23 ± 1.39	1.32
FB_2	3 (30.0)	70.0	1.87	2.65	2.15 ± 0.43	1.94	0.65 ± 1.06	0
HT-2	9 (90.0)	10.0	1.62	2.74	2.06 ± 0.39	1.98	1.86 ± 0.75	1.92
T-2	5 (50.0)	50.0	0.56	2.89	1.68 ± 1.08	1.91	0.84 ± 1.14	0.28
OTA	6 (60.0)	40.0	0.52	1.54	0.80 ± 0.4	0.64	0.48 ± 0.51	0.52
ZEN	5 (50.0)	50.0	0.90	1.83	1.13 ± 0.4	0.96	0.56 ± 0.65	0.45
BEA	9 (90.0)	10.0	0.83	2.92	1.13 ± 0.67	0.90	1.02 ± 0.73	0.89
DON	1 (10.0)	90.0	12.61	12.61	12.61	12.61	1.26 ± 3.99	0
ENNB	<LOD[c]	100.0	<LOD[c]	<LOD[c]	<LOD[c]	<LOD[c]	0	0
$ENNB_1$	4 (40.0)	60.0	0.21	0.24	0.23 ± 0.01	0.23	0.09 ± 0.12	0
ENNA	9 (90.0)	10.0	0.87	0.91	0.89 ± 0.01	0.89	0.80 ± 0.28	0.89
$ENNA_1$	9 (90.0)	10.0	0.68	0.79	0.73 ± 0.05	0.72	0.66 ± 0.24	0.72

[a] AFB_1: aflatoxin B_1; AFB_2: aflatoxin B_2; AFG_1: aflatoxin G_1; AOH: alternariol; AME: alternariol monomethyl ether; TEN: tentoxin; FB_1: fumonisin B_1; FB_2: fumonisin B_2; OTA: ochratoxin A; ZEN: zearalenone; BEA: beauvericin; DON: deoxynivalenol; ENNB: enniatin B; $ENNB_1$: enniatin B_1; ENNA: enniatin A; $ENNA_1$: enniatin A_1.
[b] For the calculation, results below the LOD and/or LOQ were set as zero.
[c] Food categories where mycotoxins were not detected were indicated as below the limit of detection (<LOD). STD: Standard Deviation. LCD: Left-Censored Data.

Table 2
Occurrence, percentage of left-censored data, average, median, and range of contamination values for the quantified mycotoxins (>LOQ) and the average and median values for the total mycotoxins found in legume-based meat alternatives (LBMAs) ($n = 30$).

Mycotoxin[a]	Occurrence, (%)	% of LCD	Minimum level, μg kg^{-1}	Maximum level, μg kg^{-1}	Average contamination level (quant.) ± STD, μg kg^{-1}	Median contamination level (quant.), μg kg^{-1}	Average contamination level (total)[b] ± STD, μg kg^{-1}	Median contamination level (total)[b], μg kg^{-1}
AFB_1	20 (66.7)	33.3	0.45	2.10	0.67 ± 0.39	0.53	0.44 ± 0.45	0.47
AFB_2	24 (80.0)	20.0	0.54	1.84	0.70 ± 0.31	0.57	0.56 ± 0.39	0.55
AFG_1	10 (33.3)	66.7	0.66	2.62	1.01 ± 0.39	0.84	0.31 ± 0.58	0
AFG_2	12 (40.0)	60.0	0.46	1.46	0.80 ± 0.33	0.67	0.32 ± 0.45	0
AOH	24 (80.0)	20.0	1.02	3.05	1.62 ± 0.54	1.48	1.30 ± 0.81	1.37
AME	25 (83.3)	16.7	0.32	2.25	0.58 ± 0.46	0.39	0.48 ± 0.47	0.38
TEN	21 (70.0)	30.0	0.63	20.81	2.47 ± 0.78	0.99	1.73 ± 4.13	0.78
FB_1	20 (66.7)	33.3	1.28	4.08	2.03 ± 0.68	1.80	1.35 ± 1.16	1.38
FB_2	17 (56.7)	43.3	1.89	2.25	1.99 ± 0.09	2.00	1.13 ± 1.01	1.90
HT-2	19 (63.3)	36.7	0.90	7.14	2.68 ± 1.25	2.28	1.70 ± 1.76	1.62
T-2	8 (26.7)	73.3	0.92	5.18	1.66 ± 1.11	1.13	0.44 ± 1.03	0
OTA	15 (50.0)	50.0	0.55	1.11	0.76 ± 0.20	0.71	0.38 ± 0.41	0.28
ZEN	21 (70.0)	30.0	0.86	1.79	1.03 ± 0.26	0.94	0.72 ± 0.53	0.89
BEA	30 (100)	0.0	0.79	5.30	1.10 ± 0.85	0.86	1.10 ± 0.85	0.86
DON	2 (6.7)	93.3	25.10	32.32	28.71 ± 3.10	28.71	1.91 ± 7.35	0
ENNB	2 (6.7)	93.3	0.75	4.21	2.48 ± 1.45	2.48	0.17 ± 0.78	0
$ENNB_1$	6 (20.0)	80.0	0.06	2.90	0.78 ± 0.11	0.27	0.15 ± 0.18	0
ENNA	29 (96.7)	3.3	0.87	1.23	0.91 ± 0.07	0.90	0.88 ± 0.28	0.90
$ENNA_1$	29 (96.7)	3.3	0.66	1.96	0.77 ± 0.25	0.70	0.74 ± 0.85	0.69

[3]Food categories where mycotoxins were not detected were indicated as below the limit of detection (<LOD). STD: Standard Deviation; LCD: Left-Censored Data.
[a] AFB_1: aflatoxin B_1; AFB_2: aflatoxin B_2; AFG_1: aflatoxin G_1; AOH: alternariol; AME: alternariol monomethyl ether; TEN: tentoxin; FB_1: fumonisin B_1; FB_2: fumonisin B_2; OTA: ochratoxin A; ZEN: zearalenone; BEA: beauvericin; DON: deoxynivalenol; ENNB: enniatin B; $ENNB_1$: enniatin B_1; ENNA: enniatin A; $ENNA_1$: enniatin A_1.
[b] For the calculation, results below the LOD and/or LOQ were set as zero.

The AFs had a prevalence between 9.4 and 49.1 % and the quantified concentration levels were highest in OBBs in the range of 0.2–0.6 μg L^{-1}, while OTA had similar values across all three types of plant-based beverages between 0.09 and 0.70 μg L^{-1}.

Among *Fusarium* toxins, FBs were primarily found in ABBs and SBBs in up to 67.7 % of samples with mean quantified values between 0.25 and 0.37 μg L^{-1}. On the other hand, type A trichothecenes HT-2 and T-2 were mainly found in OBBs, with prevalence values of 94.7 % and 59.6 %, respectively.

The widespread type B trichothecene DON was less prevalent (33.3 %), and it was found at an average quantified contamination value of 6.99 μg L^{-1}, indicating in general a lower concern related to DON occurrence in PBBs.

Regarding the non-regulated *Fusarium* toxins ENNs and BEA, their occurrence was observed in almost all the OBBs, although at low concentration levels. They were also prevalent in ABBs, although low $ENNB_1$ and $ENNA_1$ prevalences were reported (6.3, and 12.5 %, respectively). Regarding SBBs, only BEA was found (prevalence rate

Table 3
Occurrence, percentage of left-censored data, average, median, and range of contamination values for the quantified mycotoxins (>LOQ) and the average and median values for the total mycotoxins found in legume + cereal-based meat alternatives (LCBMAs) ($n = 27$).

Mycotoxin[a]	Occurrence, (%)	% of LCD	Minimum level, μg kg^{-1}	Maximum level, μg kg^{-1}	Average contamination level (quant.) ± STD, μg kg^{-1}	Median contamination level (quant.), μg kg^{-1}	Average contamination level (total)[b] ± STD, μg kg^{-1}	Median contamination level (total)[b], μg kg^{-1}
AFB_1	18 (66.7)	33.3	0.45	1.02	0.61 ± 0.18	0.55	0.41 ± 0.33	0.47
AFB_2	17 (63.0)	37.0	0.54	1.53	0.74 ± 0.33	0.56	0.46 ± 0.45	0.54
AFG_1	14 (51.9)	48.1	0.65	1.66	0.92 ± 0.36	0.73	0.48 ± 0.53	0.65
AFG_2	15 (55.6)	44.4	0.47	1.74	0.87 ± 0.33	0.78	0.43 ± 0.46	0.49
AOH	21 (77.8)	22.2	1.14	4.72	2.22 ± 0.9	2.28	1.72 ± 1.27	1.69
AME	26 (96.3)	3.7	0.31	1.05	0.47 ± 0.17	0.41	0.45 ± 0.19	0.41
TEN	22 (81.5)	18.5	0.64	2.03	1.17 ± 0.41	1.20	0.95 ± 0.59	0.90
FB_1	21 (77.8)	22.2	1.24	3.66	2.22 ± 0.75	1.90	1.73 ± 1.15	1.80
FB_2	20 (74.1)	25.9	1.87	2.51	2.03 ± 0.16	1.95	1.51 ± 0.92	1.94
HT-2	16 (59.3)	40.7	0.82	4.79	2.39 ± 0.67	2.12	1.41 ± 1.51	1.06
T-2	9 (33.3)	66.7	0.68	2.47	1.43 ± 0.21	1.25	0.48 ± 0.78	0
OTA	17 (63.0)	37.0	0.54	3.19	1.15 ± 0.78	0.69	0.72 ± 0.83	0.59
ZEN	21 (77.8)	22.2	0.89	1.90	1.13 ± 0.28	1.03	0.88 ± 0.54	0.96
BEA	27 (100.0)	0.0	0.80	2.47	1.07 ± 0.36	0.98	1.07 ± 0.36	0.98
DON	<LOD[c]	100.0	<LOD[c]	<LOD[b]	<LOD[c]	<LOD[c]	0	0
ENNB	5 (18.5)	81.5	0.24	0.75	0.53 ± 0.25	0.66	0.10 ± 0.23	0
$ENNB_1$	13 (48.1)	41.9	0.13	1.46	0.66 ± 0.38	0.61	0.32 ± 0.42	0
ENNA	27 (100.0)	0.0	0.87	1.68	1.05 ± 0.26	0.92	1.05 ± 0.26	0.92
$ENNA_1$	27 (100.0)	0.0	0.66	1.54	0.88 ± 0.25	0.75	0.88 ± 0.25	0.72

[a] AFB_1: aflatoxin B_1; AFB_2: aflatoxin B_2; AFG_1: aflatoxin G_1; AOH: alternariol; AME: alternariol monomethyl ether; TEN: tentoxin; FB_1: fumonisin B_1; FB_2: fumonisin B_2; OTA: ochratoxin A; ZEN: zearalenone; BEA: beauvericin; DON: deoxynivalenol; ENNB: enniatin B; $ENNB_1$: enniatin B_1; ENNA: enniatin A; $ENNA_1$: enniatin A_1.
[b] For the calculation, results below the LOD and/or LOQ were set as zero.
[c] Food categories where mycotoxins were not detected were indicated as below the limit of detection (<LOD). STD: Standard Deviation LCD: Left-Censored Data.

Table 4
Occurrence, percentage of left-censored data, average, median, and range of contamination values for the quantified mycotoxins (>LOQ) and the average and median values for the total mycotoxins found in legume + vegetable-based meat alternatives (LVBMAs) ($n = 25$).

Mycotoxin[a]	Occurrence, (%)	% of LCD	Minimum level, μg kg^{-1}	Maximum level, μg kg^{-1}	Average contamination level (quant.) ± STD, μg kg^{-1}	Median contamination level (quant.), μg kg^{-1}	Average contamination level (total)[b] ± STD, μg kg^{-1}	Median contamination level (total)[b], μg kg^{-1}
AFB_1	16 (64.0)	36.0	0.45	2.34	0.79 ± 0.55	0.59	0.50 ± 0.58	0.46
AFB_2	17 (68.0)	32.0	0.54	2.29	0.85 ± 0.49	0.68	0.58 ± 0.57	0.57
AFG_1	9 (36.0)	64.0	0.67	4.84	1.46 ± 0.31	0.93	0.53 ± 1.04	0
AFG_2	14 (56.0)	44.0	0.57	4.02	1.20 ± 0.90	0.96	0.67 ± 0.90	0.58
AOH	18 (72.0)	28.0	1.18	2.79	1.69 ± 0.46	1.51	1.22 ± 0.87	1.35
AME	21 (84.0)	16.0	0.32	1.06	0.43 ± 0.16	0.40	0.36 ± 0.22	0.38
TEN	21 (84.0)	16.0	0.68	7.07	1.27 ± 0.36	0.92	1.07 ± 1.33	0.85
FB_1	19 (76.0)	24.0	1.24	3.04	1.67 ± 0.48	1.59	1.27 ± 0.84	1.37
FB_2	19 (76.0)	24.0	1.87	2.30	1.99 ± 0.11	1.96	1.51 ± 0.87	1.93
HT-2	15 (60.0)	40.0	1.10	5.23	2.51 ± 1.05	2.39	1.51 ± 1.49	1.53
T-2	16 (64.0)	36.0	0.65	4.93	1.66 ± 0.49	1.27	1.06 ± 1.22	0.86
OTA	19 (76.0)	24.0	0.53	2.54	0.98 ± 0.55	0.83	0.74 ± 0.60	0.69
ZEN	19 (76.0)	24.0	0.84	3.42	1.17 ± 0.48	1.02	0.89 ± 0.71	0.94
BEA	25 (100.0)	0.0	0.80	2.98	1.09 ± 0.58	0.90	1.09 ± 0.48	0.90
DON	<LOD[c]	100.0	<LOD[c]	<LOD[c]	<LOD[c]	<LOD[c]	0	0
ENNB	2 (8.0)	92.0	0.64	5.79	3.19 ± 0.60	3.19	0.25 ± 1.15	0
$ENNB_1$	3 (12.0)	88.0	0.14	2.77	1.43 ± 0.32	1.38	0.74 ± 0.61	0
ENNA	21 (84.0)	16.0	0.87	1.07	0.90 ± 0.05	0.89	0.76 ± 0.34	0.88
$ENNA_1$	21 (84.0)	16.0	0.66	1.44	0.74 ± 0.19	0.68	0.62 ± 0.33	0.68

[a] AFB_1: aflatoxin B_1; AFB_2: aflatoxin B_2; AFG_1: aflatoxin G_1; AOH: alternariol; AME: alternariol monomethyl ether; TEN: tentoxin; FB_1: fumonisin B_1; FB_2: fumonisin B_2; OTA: ochratoxin A; ZEN: zearalenone; BEA: beauvericin; DON: deoxynivalenol; ENNB: enniatin B; $ENNB_1$: enniatin B_1; ENNA: enniatin A; $ENNA_1$: enniatin A_1.
[b] For the calculation, results below the LOD and/or LOQ were set as zero.
[c] Food categories where mycotoxins were not detected were indicated as below the limit of detection (<LOD). STD: Standard Deviation. LCD: Left-Censored Data.

100 %). Notably, the non-regulated mycotoxins ENNs and BEA have shown a high prevalence in PBBs, although at generally low concentration levels.

A similar trend was found for the non-regulated *Alternaria* toxins, although their distribution varied according to the raw material used in the manufacture.

3.3. Pairwise comparisons of the mycotoxin levels found in plant-based meat and plant-based beverages

Due to the high frequency of positive samples and occurrence levels found in the samples from this study, we wanted to check if any significant differences exist between and within the PBMAs and PBBs (Fig. 1). This may help in drawing hypothesis about the raw materials mainly contributing to single/group mycotoxin occurrence.

Within product categories, several differences can be observed. In

Table 5
Occurrence, percentage of left-censored data, average, median, and range of contamination values for the quantified mycotoxins (>LOQ) and the average and median values for the total mycotoxins found in oat-based beverages (OBBs) ($n = 57$).

Mycotoxin[a]	Occurrence, (%)	% of LCD	Minimum level, μg L^{-1}	Maximum level, μg L^{-1}	Average contamination level (quant.) ± STD, μg L^{-1}	Median contamination level (quant.), μg L^{-1}	Average contamination level (total)[b] ± STD, μg L^{-1}	Median contamination level (total)[b], μg L^{-1}
AFB_1	19 (33.3)	66.7	0.23	0.57	0.25 ± 0.08	0.23	0.09 ± 0.12	0
AFB_2	28 (49.1)	50.9	0.25	0.36	0.26 ± 0.02	0.26	0.13 ± 0.14	0.13
AFG_1	8 (14)	86.0	0.32	0.35	0.33 ± 0.01	0.33	0.05 ± 0.09	0
AFG_2	16 (28.1)	71.9	0.17	0.50	0.54 ± 0.11	0.26	0.04 ± 0.01	0
AOH	2 (3.5)	96.5	0.19	0.96	0.58 ± 0.35	0.58	0.02 ± 0.06	0
AME	42 (73.7)	31.6	0.05	0.12	0.06 ± 0.01	0.06	0.04 ± 0.03	0.05
TEN	39 (68.4)	26.3	0.22	0.38	0.27 ± 0.04	0.26	0.20 ± 0.12	0.25
FB_1	19 (33.3)	66.7	0.34	0.52	0.39 ± 0.05	0.37	0.14 ± 0.16	0
FB_2	14 (24.6)	75.4	0.35	0.38	0.36 ± 0.05	0.36	0.09 ± 0.14	0
HT-2	54 (94.7)	5.3	0.30	5.90	1.18 ± 0.48	0.64	1.14 ± 1.12	0.64
T-2	34 (59.6)	40.4	0.16	3.14	0.66 ± 0.32	0.49	0.38 ± 0.54	0.18
OTA	30 (52.6)	47.4	0.18	0.35	0.20 ± 0.04	0.19	0.11 ± 0.11	0.19
ZEN	24 (42.1)	57.9	0.20	0.38	0.24 ± 0.05	0.22	0.10 ± 0.12	0
BEA	57 (100.0)	0.0	0.12	1.68	0.55 ± 0.08	0.39	0.55 ± 0.40	0.79
DON	19 (33.3)	66.7	1.24	19.71	6.99 ± 3.92	5.15	1.84 ± 2.42	0.27
ENNB	56 (98.2)	1.8	0.11	6.17	1.50 ± 0.46	0.79	1.48 ± 1.68	0.25
$ENNB_1$	57 (100.0)	0.0	0.10	1.77	0.52 ± 0.02	0.27	0.52 ± 0.46	0.28
ENNA	56 (98.2)	1.8	0.24	0.30	0.26 ± 0.11	0.25	0.26 ± 0.04	0.39
$ENNA_1$	57 (100.0)	0.0	0.23	0.68	0.33 ± 0.12	0.27	0.33 ± 0.11	0

[3]Food categories where mycotoxins were not detected were indicated as below the limit of detection (<LOD). STD: Standard Deviation. LCD: Left-Censored Data.
[a] AFB_1: aflatoxin B_1; AFB_2: aflatoxin B_2; AFG_1: aflatoxin G_1; AOH: alternariol; AME: alternariol monomethyl ether; TEN: tentoxin; FB_1: fumonisin B_1; FB_2: fumonisin B_2; OTA: ochratoxin A; ZEN: zearalenone; BEA: beauvericin; DON: deoxynivalenol; ENNB: enniatin B; $ENNB_1$: enniatin B_1; ENNA: enniatin A; $ENNA_1$: enniatin A_1.
[b] For the calculation, results below the LOD and/or LOQ were set as zero.

Table 6
Occurrence, percentage of left-censored data, average, median, and range of contamination values for the quantified mycotoxins (>LOQ) and the average and median values for the total mycotoxins found in almond/nuts-based beverages (ABBs) ($n = 32$).

Mycotoxin[a]	Occurrence, (%)	% of LCD	Minimum level, μg L^{-1}	Maximum level, μg L^{-1}	Average contamination level (quant.) ± STD, μg L^{-1}	Median contamination level (quant.), μg L^{-1}	Average contamination level (total)[b] ± STD, μg L^{-1}	Median contamination level (total)[b], μg L^{-1}
AFB_1	3 (9.4)	90.6	0.18	0.18	0.18	0.18	0.01 ± 0.02	0
AFB_2	<LOD[c]	100.0	<LOD[c]	<LOD[c]	<LOD[c]	<LOD[c]	0	0
AFG_1	<LOD[c]	100.0	<LOD[c]	<LOD[c]	<LOD[c]	<LOD[c]	0	0
AFG_2	<LOD[c]	100.0	<LOD[c]	<LOD[c]	<LOD[c]	<LOD[c]	0	0
AOH	24 (75.0)	25.0	0.04	0.56	0.08 ± 0.5	0.05	0.06 ± 0.07	0.04
AME	10 (31.3)	69.0	0.04	0.41	0.11 ± 0.13	0.08	0.03 ± 0.05	0
TEN	4 (12.5)	87.5	0.08	0.28	0.17 ± 0.10	0.14	0.02 ± 0.04	0
FB_1	19 (59.4)	40.6	0.18	0.49	0.37 ± 0.06	0.37	0.23 ± 0.19	0.36
FB_2	20 (62.5)	37.5	0.23	0.28	0.25 ± 0.01	0.25	0.16 ± 0.12	0.24
HT-2	14 (43.7)	52.3	0.25	2.16	0.88 ± 0.47	0.72	0.16 ± 0.20	0
T-2	8 (25.0)	75.0	0.06	0.59	0.21 ± 0.09	0.15	0.05 ± 0.08	0
OTA	3 (9.4)	90.6	0.18	0.42	0.30 ± 0.12	0.30	0.03 ± 0.05	0
ZEN	4 (12.5)	87.5	0.02	0.13	0.09 ± 0.04	0.11	0.01 ± 0.03	0
BEA	32 (100.0)	0.0	0.05	2.15	0.25 ± 0.15	0.09	0.25 ± 0.35	0.09
DON	7 (21.9)	78.1	0.10	0.78	0.43 ± 0.28	0.47	0.07 ± 0.12	0
ENNB	31 (96.9)	3.1	0.02	0.67	0.06 ± 0.23	0.03	0.06 ± 0.11	0.03
$ENNB_1$	2 (6.3)	93.7	0.30	1.70	1.00 ± 0.66	1.00	0.06 ± 0.20	0
ENNA	30 (93.7)	6.3	0.02	0.52	0.04 ± 0.03	0.02	0.04 ± 0.08	0.02
$ENNA_1$	4 (12.5)	87.5	0.18	1.68	0.66 ± 0.49	0.39	0.08 ± 0.18	0

[a] AFB_1: aflatoxin B_1; AFB_2: aflatoxin B_2; AFG_1: aflatoxin G_1; AOH: alternariol; AME: alternariol monomethyl ether; TEN: tentoxin; FB_1: fumonisin B_1; FB_2: fumonisin B_2; OTA: ochratoxin A; ZEN: zearalenone; BEA: beauvericin; DON: deoxynivalenol; ENNB: enniatin B; $ENNB_1$: enniatin B_1; ENNA: enniatin A; $ENNA_1$: enniatin A_1.
[b] For the calculation, results below the LOD and/or LOQ were set as zero.
[c] Food categories where mycotoxins were not detected were indicated as below the limit of detection (<LOD). STD: Standard Deviation. LCD: Left-Censored Data.

particular, OBBs were significantly higher in BEA occurrence levels compared to ABB and SBB ($p < 0.05$), in ENNA and ENNB compared to ABB ($p < 0.05$) and T-2 compared to SBBs. This is likely due to more frequent *Fusarium* spp. occurrence in oats and cereals being a common source of mycotoxin exposure (Khan et al., 2024). For the remaining mycotoxins, no significant differences were observed within the PBBs categories.

As far as PBMAs go, no significant differences were observed among categories, likely due to the very large and interconnected formulation of final products (Supplementary Material 1).

On the contrary, differences between PBMAs and PBBs were significant for AFs, *Alternaria* toxins, trichothecenes, OTA, ZEN, ENNs, and BEA. In general, all mycotoxins had significantly higher concentrations in the meat alternatives based on cereals, legumes, vegetables, or a combination of these, when compared with the PBBs ($p < 0.05$). This observation may be attributed to the reduced diversity of raw ingredients incorporated into PBBs formulations, in combination with their higher water content.

Table 7
Occurrence, percentage of left-censored data, average, median, and range of contamination values for the quantified mycotoxins (>LOQ) and the average and median values for the total mycotoxins found in soy-based beverages (SBBs) (n = 31).

Mycotoxin[a]	Occurrence, (%)	% of LCD	Minimum level, μg L^{-1}	Maximum level, μg L^{-1}	Average contamination level (quant.) ± STD, μg L^{-1}	Median contamination level (quant.), μg L^{-1}	Average contamination level (total)[b] ± STD, μg L^{-1}	Median contamination level (total)[b], μg L^{-1}
AFB_1	11 (35.5)	64.5	0.18	0.18	0.18	0.18	0.03 ± 0.02	0
AFB_2	19 (61.3)	38.7	0.10	0.14	0.11 ± 0.01	0.10	0.07 ± 0.05	0.10
AFG_1	9 (29.0)	71.0	0.30	0.34	0.32 ± 0.03	0.32	0.05 ± 0.06	0
AFG_2	<LOD[c]	100.0	<LOD[c]	<LOD[c]	<LOD[c]	<LOD[c]	0	0
AOH	17 (54.8)	45.2	0.09	0.10	0.09 ± 0.01	0.09	0.03 ± 0.03	0.03
AME	5 (16.1)	83.9	0.03	0.15	0.09 ± 0.04	0.09	0.003 ± 0.005	0.03
TEN	19 (61.3)	38.7	0.04	0.15	0.07 ± 0.04	0.05	0.03 ± 0.03	0.01
FB_1	21 (67.7)	22.3	0.27	0.37	0.30 ± 0.03	0.28	0.20 ± 0.14	0.28
FB_2	17 (54.8)	45.2	0.26	0.30	0.27 ± 0.01	0.26	0.15 ± 0.13	0.27
HT-2	3 (9.7)	90.3	0.07	0.36	0.19 ± 0.15	0.12	0.02 ± 0.05	0
T-2	15 (48.4)	51.6	0.06	0.21	0.10 ± 0.05	0.10	0.04 ± 0.06	0
OTA	28 (90.3)	9.7	0.09	0.70	0.18 ± 0.14	0.11	0.17 ± 0.15	0.11
ZEN	7 (22.5)	71.5	0.03	0.87	0.34 ± 0.15	0.35	0.08 ± 0.14	0
BEA	31 (100.0)	0.0	0.08	0.31	0.11 ± 0.08	0.08	0.12 0.06	0.09
DON	<LOD[c]	100.0	<LOD[c]	<LOD[c]	<LOD[c]	<LOD[c]	0	0
ENNB	<LOD[c]	100.0	<LOD[c]	<LOD[c]	<LOD[c]	<LOD[c]	0	0
$ENNB_1$	<LOD[c]	100.0	<LOD[c]	<LOD[c]	<LOD[c]	<LOD[c]	0	0
ENNA	<LOD[c]	100.0	<LOD[c]	<LOD[c]	<LOD[c]	<LOD[c]	0	0
$ENNA_1$	<LOD[c]	100.0	<LOD[c]	<LOD[c]	<LOD[c]	<LOD[c]	0	0

[a] AFB_1: aflatoxin B_1; AFB_2: aflatoxin B_2; AFG_1: aflatoxin G_1; AOH: alternariol; AME: alternariol monomethyl ether; TEN: tentoxin; FB_1: fumonisin B_1; FB_2: fumonisin B_2; OTA: ochratoxin A; ZEN: zearalenone; BEA: beauvericin; DON: deoxynivalenol; ENNB: enniatin B; $ENNB_1$: enniatin B_1; ENNA: enniatin A; $ENNA_1$: enniatin A_1.
[b] For the calculation, results below the LOD and/or LOQ were set as zero.
[c] Food categories where mycotoxins were not detected were indicated as below the limit of detection (<LOD). STD: Standard Deviation. LCD: Left-Censored Data.

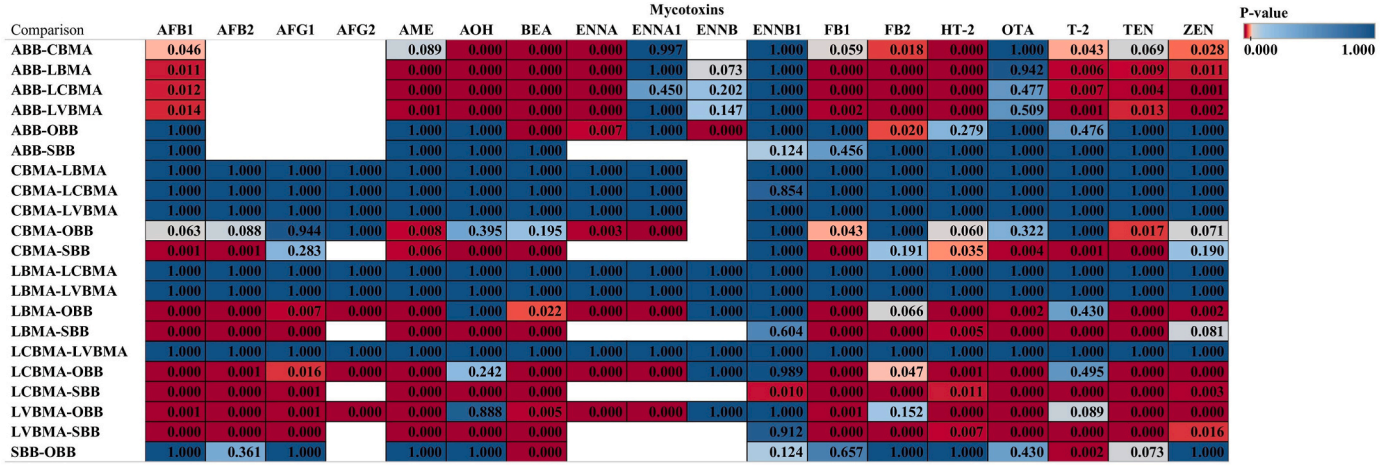

Fig. 1. Pairwise comparison between the concentration of mycotoxins in PBMAs and PBBs using the Kruskal-Wallis test. CBMAs - cereal-based plant-based meat alternatives; LBMAs - legume-based plant-based meat alternatives; LCBMAs - cereal + legume-based plant-based meat alternatives; LVBMAs - legume + vegetable-based plant-based meat alternatives; OBBs – oat-based beverage; ABBs – almond/nuts-based beverages; SBBs – soy-based beverages.

4. Discussion

This study provides the first systematic dataset on the occurrence of regulated and emerging mycotoxins in PBMAs and PBBs from the UK market. Our findings reveal that although individual concentrations were generally below EU maximum levels for cereals and related commodities, contamination was ubiquitous: all products contained at least one mycotoxin, and co-occurrence was common across all types of PBMAs and PBBs. These results carry implications for both consumer health and regulatory oversight, particularly given the increasing role of PBMAs and PBBs in UK diets.

4.1. Comparison with previous studies

The contamination levels observed in plant-based meat alternatives (PBMAs) and beverages (PBBs) from the UK market are broadly in line with previous reports across Europe and North America, although variability among studies exists due to differences in formulation and raw ingredients.

For PBMAs, the prevalence of aflatoxins (AFs) was higher in our study (up to 82.6 %) compared to PBMAs from the Italian market (39.5 %) reported by Mihalache et al. (2024), though mean quantified levels were slightly lower at 0.57–0.79 μg kg^{-1}.

OTA was detected overall in 62 % of the samples, with mean quantified values lower than those found in soy- and chickpea-based burgers from Italy (8.6 and 4.9 μg kg^{-1}, respectively) by Mihalache et al. (2023). Nonetheless, our findings are in line with levels reported by EFSA for legumes, such as chickpeas (0.10–0.79 μg kg^{-1}), soya beans (0.95–2.26 μg kg^{-1}), and soya bean flour (0.80–1.76 μg kg-1) (EFSA, 2020a). OTA was initially reported in Canada in soybean-derived products with a mean contamination value comparable to our study (0.11 μg kg^{-1}) (Kolakowski et al., 2016).

ZEN occurred in 50–77.8 % of samples with mean positive values between 1.03 and 1.13 μg kg^{-1}, notably lower than the concentrations reported in textured soy products from Germany (17 μg kg^{-1}) (Schollenberger et al., 2007) and in Italian PBMAs (5.77–6.00 μg kg^{-1}) (Mihalache et al., 2024).

FBs were commonly found across the PBMAs from this study (up to 75 %), but at lower contamination values than those reported by Mihalache et al. (2023). HT-2 and T-2 toxins were particularly frequent in cereal-based products, aligning with previous evidence of their predominance in oat and wheat matrices.

Among emerging mycotoxins, BEA had the highest prevalence being consistent with the Italian market data on PBMAs (Mihalache et al., 2024). *Alternaria* toxins (AOH, AME, TEN) showed similar patterns to those observed by Bessaire et al. (2021) in soy protein, though that study did not report specific concentrations.

Enniatins (ENNs) also exhibited high overall prevalence (93.5 %), with ENNA and $ENNA_1$ predominating, whereas Rodríguez-Carrasco et al. (2019) found ENNB and $ENNB_1$ to be dominant in soy-based burgers (quantified values ranging from 3.9 to 549.4 μg kg^{-1}).

Regarding plant-based beverages, our results are consistent with the literature in terms of both regulated and emerging mycotoxins. AFs levels in OBBs for positive samples were comparable with those reported by Miró-Abella et al. (2017), and were lower than those observed in ABBs by Torrijos et al. (2025) and Rodríguez-Cañás et al. (2023).

OTA and ZEN contamination patterns were also consistent with recent European data (Miró-Abella et al., 2017; Pavlenko et al., 2024; Rodríguez-Cañás et al., 2023; Torrijos et al., 2025), except for Juan et al. (2022), who reported higher ZEN levels in soy-based beverages (10.79 μg L^{-1}).

In our study, the maximum DON concentration (19.71 μg L^{-1}) was one order of magnitude lower than those reported in Spanish oat-based beverages (191–270 μg L^{-1}) (Hamed et al., 2017).

Finally, the widespread presence of ENNs and BEA is similar with reports across the EU and UK markets (Arroyo-Manzanares et al., 2019; Juan et al., 2022; Pavlenko et al., 2024; Rodríguez-Cañás et al., 2023; Torrijos et al., 2025). Similarly, for *Alternaria* toxins, our results are consistent with the occurrence reported in PBBs purchased from the Spanish market (Rodríguez-Cañás et al., 2023).

Overall, these comparisons indicate that the contamination levels observed in UK PBMAs and PBBs are comparable to or lower than those reported in continental Europe, yet co-occurrence of multiple mycotoxins remains a consistent and concerning feature.

4.2. Mycotoxin occurrence and co-occurrence

Although the occurrence data found for mycotoxins in PBMAs and PBBs from the UK market are low, previous risk assessment indicated that even at low levels, exposure can still lead to potential health concerns (Mihalache et al., 2024). Besides individual occurrence, the highly frequent co-occurrence of mycotoxins should be carefully considered for future risk assessments. Such a large co-occurrence could lead to potential health risks that should be further evaluated since the synergistic or additive action of the mycotoxins reported in our study has been extensively described *in vitro* (Alassane-Kpembi et al., 2017; Vejdovszky et al., 2017; Wang et al., 2020).

The large combination of mycotoxins found in both PBMAs and PBBs likely reflects the use of many ingredients in the product formulation, with each ingredient potentially being infected or co-infected by fungal pathogens or by fungal species able to produce several mycotoxins (see Supplementary Materials **6** and **7** for more details). Such a large diversity in ingredients, together with the differences in water content, is also at the base of the difference in contamination between PBMA and PBBs observed using pairwise comparison analysis. While less ingredients and at higher water-dilution are used in PBBs, PBMAs often are formulated with more than 10 ingredients (i.e., cereal flours, mixtures of vegetables, spices, etc.). In particular, the use of vegetable oils like rapeseed and sunflower oils as well as herbs and spice mixes as flavoring agents, is quite common in PBMAs and PBBs, and this could represent an additional source of mycotoxins into the final product (EFSA, 2020a; EFSA, 2020b; Junsai et al., 2021; Li et al., 2023; Puntscher et al., 2019).

4.3. Ingredient-specific contamination patterns

PBMA products collected from the UK market returned a very large diversity in ingredients and formulation, as a consequence of difficulties in overcoming technological and sensorial challenges (for details, see Supplementary Material 1). PBMAs are actually designed by combining non-textured vegetable proteins (3–10 %) and textured vegetable proteins (10–25 %), typically derived from cereal sources (i.e., wheat flour, wheat gluten, and rice flour) or legume sources (i.e., chickpeas, pea protein, and soya protein), which play a crucial role in creating the meat-analog structure (Ahmad et al., 2022; Kyriakopoulou, Dekkers, & Van der Goot, 2019; Vila-Clarà et al., 2024). While mycotoxins in cereals are largely regulated and monitored, several authors have already emphasized the lack of information regarding their occurrence in legumes used for PBMA manufacturing (Acuña-Gutiérrez et al., 2022; Mihalache et al., 2022; Pavicich et al., 2024). In addition to soybeans, other legumes such as lentils, chickpeas, and green peas are common sources for the extraction of proteins and protein hydrolysates for the production of PBMAs and PBBs, or as texturizing ingredients. Such raw materials may support fungal growth in the field or during long-term storage, as recently reported in black lentils, white beans and green peas from Germany (Kunz et al., 2020). The detection of TEN in soy protein isolates used for the development of plant-based burgers (Cutroneo et al., 2025a) confirms that contamination can occur at the ingredient level before commercial formulation. Our findings extend this observation to retail products, where multiple ingredients contribute simultaneously to mycotoxin occurrence and co-occurrence.

Although mycotoxin occurrence in PBBs collected in our study are generally low, it should be noticed that the products analyzed in this study contained a percentage of the primary raw materials ranging from 1.3 to 13.0 % in OBBs, 1–6 % in ABBs, and 2.4–15.0 % in SBBs (Supplementary Material 2). Considering the water dilution of the primary ingredients, it is surprising that AFB_1 in OBBs is often close to the maximum legislative value in cereals and cereal products (2 and 4 μg kg^{-1}, respectively) (European Commission, 2023), suggesting a low quality (or even a non-compliance) of the cereals used for the product formulation. Similar results have been observed for OTA. However, a comparison with the legislative limit is challenging since the products close to the maximum limit for products derived from unprocessed cereal grains (3.0 μg kg^{-1}) also contained other regulated ingredients, such as cocoa powder or coffee, which are commonly susceptible to OTA-producing fungi (Copetti et al., 2014; EFSA, 2020a; Jubeen et al., 2022).

Regarding the production of PBBs, plant materials (e.g. oats, rice, soy or nuts) undergo a water-soaking step, followed by grinding and filtration, before being added with flavoring ingredients and pasteurised for commercialization (Aydar et al., 2020). The long soaking step may favour the transfer of mycotoxins from the starting material to the liquid phase. Although nothing is known so far, under such conditions a further release of masked/bound mycotoxins cannot be ruled out (EFSA, 2017). This fact might explain the wide occurrence of T-2/HT-2 in OBBs, the most common PBB on the market nowadays. Oats are known to suffer from *Fusarium* spp. infection and T-2/HT-2 accumulation, according to the production system and the environmental conditions. T-2/HT-2 have been reported as the main oats mycotoxins in Europe and the UK, with relevant influence of the climate and the agronomic practices (Daud et al., 2023; Schöneberg et al., 2018).

In light of the wide presence in the market and the growing consumption among consumers (gfieurope.org, 2024a), PBBs, and in particular OBBs and SBBs, should undergo widespread screening and further risk assessment should be performed to ensure consumer health

and safety.

Currently, the maximum limits for certain mycotoxins in food and feedstuff are set at the European level in Commission Regulation (EC) 2023/915, and the UK has retained these provisions in its national legislation. However, neither PBMAs nor PBBs are included in the regulation as finished products. Regarding their ingredients, while cereals intended for human consumption are largely monitored for mycotoxins, only soybeans are monitored for OTA, although it is known that other pulses can be infected by toxicogenic fungi (Acuña-Gutiérrez et al., 2022). Also considering the increasing consumption of legumes and their large use in the formulation of plant-based products (i.e., 86 out the 92 PBMAs included in our study contained legumes), the data gaps regarding mycotoxins occurrence in legumes and pulses should be urgently tackled (Mihalache et al., 2022). Research efforts are needed also for understanding the dynamic of mycotoxin transfer and/or degradation during plant-based product manufacturing. It should be noticed that processes like conventional cooking, roasting, baking, and pasteurization have little to no effect in the mitigation of mycotoxins in cereals and pulses, while little to nothing is known so far about the effect of extrusion and hydrothermal treatment used for alternative protein flakes production. While these treatments might induce mycotoxin degradation to some extent, the potential masking effect due to the formation of bound mycotoxins cannot be ruled out in the absence of dedicated studies (Campagnollo et al., 2016; Liu et al., 2020). On the other hand, it is worth mentioning that the high level of lectin and saponin content in legumes might provide antifungal properties and reduce mycotoxin contamination (Baker et al., 2009; Lam & Ng, 2010). Environmental factors (i.e., high humidity and increased temperature) directly impact the colonization and growth of toxigenic fungi, as well as mycotoxin production, during cultivation, postharvest, and storage (Garcia-Cela et al., 2018; Nesic et al., 2015; Perincherry et al., 2019). While correlations between environmental conditions and mycotoxin contamination have been reported for various commodities, including fruits, vegetables, and cereals (Ferrigo et al., 2016; Medina et al., 2017), there is currently a lack of information regarding pulses such as those used in the production of meat and milk alternatives.

Compared to PBBs, PBMAs have a mixture of ingredients which are commonly contaminated with mycotoxins such as cereals (wheat, oat, maize, etc.) and legumes (i.e., beans, soy, peas, and chickpeas), and thus have a higher risk of mycotoxin contamination. Hence, the actual contribution of PBMAs and PBBs to dietary mycotoxin exposure is likely underestimated and may not reflect accurately the real exposure patterns in the UK.

5. Conclusions

This work represents the first comprehensive investigation of mycotoxin occurrence in 212 plant-based foods (PBMAs + PBBs) from the UK market. All PBMAs and PBBs were contaminated by at least one mycotoxin, with frequent co-occurrence of multiple mycotoxins. Among PBMAs, legume-based and mixed cereal–legume products were the most affected, with frequent detection of aflatoxins (AFB_1, AFB_2, AFG_1, AFG_2) and high occurrence of *Fusarium* toxins such as FBs, HT-2, T-2, and ZEN. CBMAs also contained DON, highlighting the broad contamination risk across ingredients. In PBBs, OBBs showed consistently high levels of type A trichothecenes (HT-2 and T-2) and FBs, while SBBs were characterized by a strikingly high prevalence of OTA (90 %). ABBs showed comparatively lower contamination, but emerging mycotoxins were frequently detected.

Even though quantified occurrence values were below regulatory levels, the high prevalence of mixtures including AFs, OTA, *Fusarium*, and *Alternaria* toxins, indicates that cumulative exposure may pose health concerns.

Our findings highlight that it is essential to extend mycotoxin monitoring efforts to include the raw primary commodities used in PBMAs and PBBs production. These data provide a foundation for assessing dietary exposure and accurate risk assessments in the UK. Policymakers and the industry should consider the changing dietary patterns and the importance of raw material control and good manufacturing practices. Ensuring the safety of plant-based foods is essential to support their role as healthy and sustainable alternatives in the ongoing dietary transitions.

CRediT authorship contribution statement

Raquel Torrijos: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Octavian Augustin Mihalache:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Andrea Patriarca:** Writing – review & editing, Conceptualization. **Angel Medina:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Chiara Dall'Asta:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodcont.2025.111910.

Abbreviations

Acetonitrile (MeCN); aflatoxin B_1 (AFB_1); aflatoxin B_2 (AFB_2); aflatoxin G_1 (AFG_1); aflatoxin G_2 (AFG_2); almond/nut-based beverage (ABB); alternariol (AOH); alternariol monomethyl ether (AME); beauvericin (BEA); cereal-based meat alternative (CBMA); seoxynivalenol (DON); enniatin A (ENNA); enniatin A_1 ($ENNA_1$); enniatin B (ENNB); enniatin B_1 ($ENNB_1$); fumonisin B_1 (FB_1); fumonisin B_2 (FB_2); legume-based meat alternative (LBMA); legumes and cereals-based meat alternative (LCBMA); legumes and vegetables-based meat alternative (LVBMA); limit of detection (LOD); limit of quantification (LOQ); magnesium sulfate ($MgSO_4$); methanol (MeOH); oat-based beverage (OBB); ochratoxin A (OTA); plant-based beverage (PBB); plant-based meat alternative (PBMA); salt-assisted liquid-liquid extraction (SALLE); soy-based beverage (SBB); tentoxin (TEN); ultra-high performance liquid chromatography coupled to mass spectrometry (UHPLC-MS/MS); zearalenone (ZEN).

Data availability

The data used is in the manuscript.

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