A Three-Year Survey on the Worldwide Occurrence of Mycotoxins in Feedstuffs and Feed

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Abstract: Between January 2009 and December 2011, a total of 7049 corn, soybean/soybean meal, wheat, dried distillers grains with solubles (DDGS) and finished feed samples were analyzed for the occurrence of aflatoxins (Afla), zearalenone (ZEN), deoxynivalenol (DON), fumonisins (FUM) and ochratoxin A (OTA). Samples were sourced in the Americas, Europe and Asia. Afla, ZEN, DON, FUM and OTA were present respectively in 33%, 45%, 59% 64% and 28% of analyzed samples between 2009 and 2011. From the 23,781 mycotoxin analyzes performed, 81% were positive for at least one mycotoxin. Results of this survey are provided by calendar year, in order to potentially show different trends on mycotoxin occurrence in distinct years: by commodity type and within the same commodity, and by region, to potentially reveal differences in mycotoxin contamination in commodities sourced in diverse regions.

Keywords: aflatoxins; deoxynivalenol; fumonisins; zearalenone; ochratoxin A; mycotoxins; occurrence; survey

1. Introduction

Mycotoxins refer to a diverse group of compounds produced by a wide range of different fungi, normally after a phase of balanced growth. Plant genetics, exposure to fungal spores, weather conditions and climate during planting, growing and harvesting, insect damage, crop management and
use of fungicides, are some of the factors that influence the growth of fungi on crops and their subsequent mycotoxin production. Mycotoxin-producing fungi are commonly sub-divided into field fungi and storage fungi; however, the actual colonization and proliferation of fungi is not clear cut, but depends on the environmental and ecological circumstances, and the resulting toxins will differ accordingly. Moisture and temperature have a major influence on mold growth and mycotoxin production. Pathogenic fungi that invade crops prior to harvest usually require higher moisture levels (200–250 g/kg) for infection than fungi that can proliferate during storage (130–180 g/kg) [1].

Interestingly, the presence of mycotoxin-producing fungi in a plant is not always conducive to contamination with mycotoxins. In order for fungi to produce these secondary metabolites, they have to be stressed by some factor [2], such as nutritional imbalance, drought or water excess.

This paper gathers information on the presence of mycotoxins in the commodities most commonly used for feed production and in finished feed through a period of 3 years. From January 2009 until December 2011, 23,781 mycotoxin analyses were performed on 7049 samples sourced in North and South America (the Americas), Europe and Asia. Middle Eastern and African samples were gathered in previously published reports [3,4] and were therefore excluded from this paper. Samples were analyzed for some or all mycotoxins: aflatoxins (Afla), zearalenone (ZEN), deoxynivalenol (DON), fumonisins (FUM) and ochratoxin A (OTA). Data is grouped for discussion as follows: per calendar year, in order to potentially show different trends in mycotoxin occurrence in distinct years; by commodity type and within the same commodity, and by region, to potentially reveal differences in mycotoxin contamination in commodities sourced in diverse regions.

2. Results and Discussion

2.1. Results by Calendar Year

Table 1 reflects the contamination of all samples, regardless of their nature, for the sum of the three years, and then separated by calendar year. Afla, ZEN, DON, FUM and OTA were respectively present in 33%, 45%, 59%, 64% and 28% of analyzed samples between 2009 and 2011. Positive samples respectively averaged contamination levels of 63, 233, 1104, 1965 and 11 ppb for these mycotoxins. When data is separated by year, these values actually do not greatly differ. Within the three years of the study, the highest level of Afla was found in a corn sample from Vietnam (maximum: 6105 ppb); two wheat samples from Australia had the highest DON (maximum: 23,278 ppb) and ZEN (maximum: 49,307 ppb) levels found, while finished feed from China and Pakistan presented the highest levels of FUM (maximum: 77,502 ppb) and OTA (maximum: 1582 ppb), respectively.

2.2. Results by Commodity and Region Sourced

Tables 2–12 present data referring to mycotoxin contamination in different feedstuffs and finished feed, globally and separated by geographical region sourced.
Table 1. Annual global trend regarding mycotoxin occurrence in corn, soybean meal (SBM), wheat, dried distillers grains with solubles (DDGS) and finished feed samples surveyed in the Americas, Europe and Asia.

| Country of origin  | Corn | Wheat | Wheat | Wheat | Corn | Wheat | Corn | Wheat | Corn | Wheat | Wheat | Wheat | Corn | Wheat | Wheat | Wheat | Corn | Wheat | Wheat | Wheat | Wheat | Wheat | Wheat | Wheat | Wheat | Wheat |
|--------------------|------|-------|-------|-------|------|-------|------|-------|------|-------|-------|-------|------|-------|-------|-------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Number of tested samples | 4,627 | 5,402 | 5,189 | 4,670 | 3,263 | 1,402 | 1,438 | 1,102 | 702 | 51 | 28 | 40 | 15 | 31 | 49 | 65 | 27 | 30 | 44 | 61 | 58 | 27 | 64 | 243 | 1,093 | 1,711 |
| Positive (%) | 33 | 45 | 59 | 64 | 28 | 40 | 45 | 244 | 130 | 47 | 63 | 65 | 120 | 816 | 1,245 | 27 | 30 | 44 | 61 | 58 | 27 | 64 | 243 | 1,093 | 1,711 |
| Average (ppb) | 63 | 233 | 1,104 | 1,965 | 11 | 15 | 120 | 794 | 1,767 | 5 | 15 | 120 | 816 | 1,245 | 27 | 30 | 44 | 61 | 58 | 27 | 64 | 243 | 1,093 | 1,711 |
| Median of positive (ppb) | 9.0 | 80.0 | 505.0 | 958.0 | 2.0 | 11.0 | 87.0 | 496.0 | 1,094.0 | 3.0 | 8.0 | 85.0 | 540.0 | 983.0 | 2.3 | 9.0 | 71.0 | 486.0 | 849.0 | 2.0 |
| 1st quartile of positive (ppb) | 2.1 | 40.0 | 256.0 | 425.8 | 0.9 | 3.0 | 45.0 | 270.3 | 486.0 | 1.5 | 2.0 | 40.7 | 274.0 | 447.0 | 0.9 | 2.0 | 37.0 | 222.3 | 360.0 | 0.9 |
| 3rd quartile of positive (ppb) | 41.0 | 198.3 | 1,055.0 | 2,254.3 | 6.0 | 43.5 | 182.0 | 934 | 3,064 | 5.7 | 34.4 | 226.0 | 1,255.8 | 2,225.0 | 5.6 | 52.0 | 186.0 | 1,000.8 | 2,011.3 | 6.8 |

Table 2. Mycotoxin occurrence in corn samples surveyed in North and South America and in Central and Southern Europe (no corn samples sourced in Northern Europe were surveyed).

| Commodity found | North America | South America | Central Europe | Southern Europe |
|-----------------|---------------|---------------|----------------|-----------------|
| Number of tested samples | 375 | 395 | 390 | 466 | 126 | 809 | 321 | 322 | 807 | 147 | 16 | 379 | 535 | 30 | 21 | 42 | 52 | 59 | 48 | 31 |
| Positive (%) | 26 | 29 | 79 | 39 | 10 | 25 | 43 | 17 | 92 | 12 | 31 | 39 | 72 | 60 | 10 | 36 | 21 | 47 | 90 | 29 |
| Average of positive (ppb) | 67 | 251 | 1,085 | 1,357 | 5 | 7 | 176 | 214 | 3,226 | 133 | 2 | 123 | 1,421 | 2,180 | 2 | 9 | 290 | 985 | 2,271 | 15 |
| Maximum (ppb) | 920 | 4,787 | 24,900 | 22,900 | 18 | 273 | 1,800 | 939 | 53,700 | 355 | 3 | 849 | 26,121 | 7,680 | 3 | 4 | 1,546 | 3,851 | 11,050 | 46 |
| Average (ppb) | 17 | 74 | 857 | 533 | 1 | 2 | 75 | 37 | 2,966 | 16 | 1 | 47 | 1,028 | 1,308 | 0 | 3 | 61 | 468 | 2,035 | 4 |
| Median of positive (ppb) | 10.1 | 86.4 | 565.0 | 490.0 | 2.3 | 1.8 | 87.1 | 172.0 | 2,008.0 | 71.3 | 1.5 | 78.5 | 716.0 | 684.0 | 2.4 | 4.0 | 166.0 | 523.0 | 1,407.0 | 9.3 |
| 1st quartile of positive (ppb) | 2.6 | 59.9 | 300.0 | 280.0 | 1.4 | 1.0 | 40.4 | 140.0 | 859.5 | 20.0 | 1.4 | 42.3 | 431.5 | 276.3 | 2.2 | 1.6 | 73.5 | 308.5 | 756.0 | 1.5 |
| 3rd quartile of positive (ppb) | 62.3 | 167.8 | 931.0 | 1,160.5 | 3.1 | 4.9 | 222.0 | 241.4 | 3,890.0 | 274.8 | 1.8 | 155.0 | 1,575.5 | 4,503.8 | 2.5 | 11.6 | 275.5 | 705.0 | 3,265.5 | 28.8 |
Table 3. Mycotoxin occurrence in corn samples surveyed in North, South-East and South Asia and in Oceania.

| CORN | North Asia | South-East Asia | South Asia | Oceania |
|------|------------|-----------------|------------|---------|
|      | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA |
| Number of tested samples | 447 | 470 | 477 | 443 | 420 | 330 | 319 | 218 | 326 | 218 | 108 | 108 | 106 | 108 | 107 | 11 | 11 | 11 | 11 | 11 |
| Positive (%) | 12 | 67 | 92 | 75 | 10 | 71 | 20 | 45 | 83 | 12 | 82 | 9 | 22 | 74 | 27 | 18 | 27 | 27 | 64 | 9 |
| Average of positive (ppb) | 114 | 437 | 1,154 | 2,816 | 4 | 146 | 288 | 307 | 1,568 | 9 | 240 | 269 | 278 | 845 | 31 | 3 | 636 | 182 | 2,823 | 1 |
| Maximum (ppb) | 4,687 | 7,446 | 15,073 | 23,499 | 19 | 6,105 | 2,601 | 4,805 | 19,289 | 80 | 2,230 | 1,099 | 1,150 | 6,196 | 400 | 5 | 1,251 | 249 | 5,438 | 1 |
| Average (ppb) | 13 | 292 | 1,062 | 2,111 | 0 | 104 | 59 | 140 | 1,293 | 1 | 197 | 25 | 60 | 626 | 8 | 1 | 173 | 50 | 1,796 | 0 |
| Median of positive (ppb) | 7.0 | 176.0 | 640.0 | 1,518.5 | 1.4 | 38.0 | 97.0 | 182.0 | 1,033.0 | 3.0 | 96.0 | 78.5 | 190.0 | 541.0 | 7.4 | 3.0 | 626.0 | 179.0 | 2,344.0 | 1.2 |
| 1st quartile of positive (ppb) | 2.0 | 63.9 | 309.5 | 592.5 | 0.7 | 11.0 | 51.0 | 103.5 | 552.0 | 0.75 | 13.0 | 67.3 | 104.0 | 293.3 | 2.0 | 2.0 | 328.0 | 148.5 | 1,453.0 | 1.2 |
| 3rd quartile of positive (ppb) | 35.5 | 435.0 | 1,444.5 | 3,593.5 | 4.1 | 137.5 | 206.0 | 351.5 | 1,720.0 | 6.3 | 312.0 | 174.3 | 348.5 | 796.0 | 15.0 | 4.0 | 938.5 | 214.0 | 4,023.0 | 1.2 |

Table 4. Mycotoxin occurrence in soybean meal samples surveyed in North and South America and in Central and Southern Europe (no soybean meal samples sourced in Northern Europe were surveyed).

| SOYBEAN MEAL | North America | South America | Central Europe | Southern Europe |
|--------------|---------------|---------------|----------------|-----------------|
|              | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA |
| Number of tested samples | 74 | 50 | 45 | 46 | 18 | 60 | 53 | 55 | 60 | 51 | 8 | 31 | 43 | 2 | 3 | 23 | 23 | 25 | 21 | 22 |
| Positive (%) | 1 | 10 | 18 | 0 | 17 | 8 | 34 | 29 | 5 | 10 | 38 | 6 | 21 | 0 | 33 | 22 | 0 | 24 | 29 | 18 |
| Average of positive (ppb) | 2 | 83 | 1,007 | - | 4 | 1 | 129 | 208 | 230 | 5 | 1 | 36 | 470 | - | 21 | 2 | - | 419 | 1,017 | 1 |
| Maximum (ppb) | 2 | 144 | 5,500 | - | 6 | 1 | 807 | 428 | 315 | 10 | 1 | 56 | 741 | - | 21 | 3 | - | 908 | 5,088 | 1 |
| Average (ppb) | 0 | 8 | 179 | - | 1 | 0 | 44 | 61 | 12 | 0 | 0 | 2 | 98 | - | 7 | 0 | - | 101 | 291 | 0 |
| Median of positive (ppb) | 2.0 | 50.8 | 187.0 | - | 4.6 | 1.0 | 81.0 | 197.0 | 274.0 | 1.0 | 1.2 | 35.7 | 450.0 | - | 21.4 | 1.8 | - | 338.5 | 95.0 | 1.2 |
| 1st quartile of positive (ppb) | 2.0 | 45.3 | 143.0 | - | 3.2 | 1.0 | 52.3 | 83.8 | 188.0 | 0.9 | 1.2 | 25.6 | 363.0 | - | 21.4 | 1.4 | - | 286.5 | 90.3 | 0.9 |
| 3rd quartile of positive (ppb) | 2.0 | 142.4 | 733.8 | - | 5.2 | 1.0 | 130.3 | 291.8 | 294.5 | 10.4 | 1.3 | 45.9 | 494.0 | - | 21.4 | 2.7 | - | 428.0 | 510.8 | 1.3 |
Table 5. Mycotoxin occurrence in soybean meal samples surveyed in North, South-East and South Asia and in Oceania.

|                 | North Asia | South-East Asia | South Asia | Oceania |
|-----------------|------------|-----------------|------------|---------|
| **SOYBEAN MEAL** |            |                 |            |         |
| Number of tested samples | 36 | 109 | 16 | 3 |
| Positive (%) | 6 | 22 | 63 | 3 |
| Average of positive (ppb) | 3 | 5 | 4 | 3 |
| Maximum (ppb) | 3 | 74 | 7 | 3 |
| Average (ppb) | 0 | 1 | 2 | 3 |
| Median of positive (ppb) | 2.8 | 1.0 | 2.0 | 1.0 |
| 1st quartile of positive (ppb) | 2.7 | 1.0 | 1.0 | 1.0 |
| 3rd quartile of positive (ppb) | 2.9 | 3.25 | 6.6 | 4.1 |

Table 6. Mycotoxin occurrence in wheat/wheat bran samples surveyed in North and South America.

|                 | North America | South America |
|-----------------|---------------|---------------|
| **WHEAT/BRAN**  |               |               |
| Number of tested samples | 15 | 40 |
| Positive (%) | 20 | 40 |
| Average of positive (ppb) | 5 | 5 |
| Maximum (ppb) | 9 | 3 |
| Average (ppb) | 1 | 3 |
| Median of positive (ppb) | 4.1 | 2.6 |
| 1st quartile of positive (ppb) | 2.8 | 2.6 |
| 3rd quartile of positive (ppb) | 6.6 | 2.6 |
Table 7. Mycotoxin occurrence in wheat/wheat bran samples surveyed in Northern, Central and Southern Europe.

|                     | Northern Europe |                     | Central Europe |                     | Southern Europe |
|---------------------|-----------------|---------------------|----------------|---------------------|-----------------|
|                     | Afla ZEN DON FUM OTA | Afla ZEN DON FUM OTA | Afla ZEN DON FUM OTA |                     | Afla ZEN DON FUM OTA |
| Number of tested samples | 1 71 71 1 2 | 13 256 436 9 22 | 14 17 24 10 13 |
| Positive (%)         | 0 15 55 0 0 | 31 12 55 33 23 | 43 0 38 30 8 |
| Average of positive (ppb) | - 109 1,058 - | 2 89 1,534 268 69 | 2 - 1,204 386 1 |
| Maximum (ppb)        | - 233 7,341 - | 2 336 49,000 450 331 | 6 - 3,505 925 1 |
| Average (ppb)        | - 17 581 - | 0 10 848 89 16 | 1 - 452 116 0 |
| Median of positive (ppb) | - 96.0 641.0 | 1.6 65.0 514.0 246.0 3.8 | 1.6 - 716.0 151.0 0.7 |
| 1st quartile of positive (ppb) | - 62.5 442.0 | 1.2 47.3 361.0 177.5 2.8 | 1.4 - 503.0 117.0 0.7 |
| 3rd quartile of positive (ppb) | - 131.0 932.5 | 2.0 122.8 960.0 348.0 5.4 | 1.8 - 1,864.0 538.0 0.7 |

Table 8. Mycotoxin occurrence in wheat/wheat bran samples surveyed in North and South-East Asia and in Oceania (no wheat/bran samples sourced in South Asia were surveyed).

|                     | North Asia | South-East Asia | Oceania |
|---------------------|------------|-----------------|---------|
|                     | Afla ZEN DON FUM OTA | Afla ZEN DON FUM OTA | Afla ZEN DON FUM OTA |
| Number of tested samples | 76 72 75 73 67 | 40 40 40 40 40 | 109 115 109 109 108 |
| Positive (%)         | 7 42 87 11 22 | 3 40 65 5 30 | 5 28 48 12 8 |
| Average of positive (ppb) | 6 74 922 371 2 | 1 531 2,251 172 6 | 3 1,546 5,046 269 2 |
| Maximum (ppb)        | 20 465 5,331 874 7 | 1 6,641 41,439 292 30 | 7 23,278 49,307 1,196 4 |
| Average (ppb)        | 0 31 799 41 0 | 0 212 1,463 9 2 | 0 430 2,407 32 0 |
| Median of positive (ppb) | 3.3 47.7 426.0 297.5 1.0 | 1 52.5 198.5 172.0 3.9 | 2.0 179.5 719.0 196.0 1.6 |
| 1st quartile of positive (ppb) | 1.0 20.6 168.0 191.5 0.7 | 1 44.8 97.0 112.0 1.4 | 2.0 76.8 90.0 120.0 1.0 |
| 3rd quartile of positive (ppb) | 3.6 82.1 1,279.0 471.3 2.0 | 1 216.8 1,483.3 232.0 5.7 | 5.0 351.0 5,870.3 216.0 3.7 |
Table 9. Mycotoxin occurrence in DDGS samples surveyed in North America, North and South-East Asia and in Oceania.

| DDGS   | North America | North Asia | South-East Asia | Oceania |
|--------|---------------|------------|-----------------|---------|
|        | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA |
| Number of tested samples | 42   | 80  | 80  | 62  | 24  | 68   | 71  | 76  | 58  | 61  | 22   | 22   | 22  | 22  | 22  | 22  | 10  | 10  | 10  | 10  | 10  |
| Positive (%) | 29   | 80  | 96  | 84  | 33  | 21   | 85  | 93  | 62  | 39  | 0    | 100  | 100 | 100 | 100 | 41  | 0   | 10  | 20  | 20  | 20  |
| Average of positive (ppb) | 7    | 194 | 2,186 | 1,329 | 2  | 54   | 321 | 3,068 | 1,596 | 6   | -    | 286  | 3,618 | 1,481 | 2   | -   | 51  | 1,318 | 2,138 | 5  |
| Maximum (ppb) | 14   | 849 | 10,100 | 6,400 | 4  | 340  | 2,319 | 15,597 | 9,782 | 26  | -    | 1,179 | 19,096 | 8,449 | 4.2 | -   | 51  | 2,577 | 2,837 | 6  |
| Average (ppb) | 2    | 156 | 2,104 | 1,115 | 1  | 11   | 272 | 2,866 | 991  | 3   | -    | 286  | 3,618 | 1,481 | 1   | -   | 5   | 264  | 428  | 1  |
| Median of positive (ppb) | 6.6  | 138.5 | 1,520.0 | 840.0 | 1.4 | 34.0 | 171.0 | 2,390.0 | 490.0 | 3.1 | -    | 163.5 | 2,127.5 | 848  | 1.8 | -   | 51  | 1,317.5 | 2,138.0 | 5.0 |
| 1st quartile of positive (ppb) | 4.3  | 95.7 | 960.0 | 462.0 | 1.2 | 21.1 | 56.6 | 1,152.5 | 242.3 | 1.6 | -    | 86.0  | 970.3 | 419.3 | 0.8 | -   | 51  | 687.8 | 1,788.5 | 4.5 |
| 3rd quartile of positive (ppb) | 9.4  | 222.9 | 2,600.0 | 1,534.5 | 2.3 | 43.1 | 389.0 | 4,212.0 | 1,421.3 | 8.5 | -    | 313.5 | 4,570.0 | 1,923.0 | 3.6 | -   | 51  | 1,947.3 | 2,487.5 | 5.5 |

Table 10. Mycotoxin occurrence in finished feed samples surveyed in North and South America.

| FINISHED FEED | North America | South America |
|---------------|---------------|---------------|
|               | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA |
| Number of tested samples | 21   | 42  | 55  | 32  | 8   | 203  | 119 | 130 | 224 | 49  | 29   | 299 | 1,718 | 2,369 | -   | 6   | 201 | 250 | 1,665 | 26  |
| Positive (%) | 24   | 52  | 65  | 47  | 0   | 26   | 57  | 13  | 94  | 12  | 56   | 1,710 | 6,100 | 11,400 | -   | 83  | 3,570 | 808 | 10,380 | 49  |
| Average of positive (ppb) | 29   | 299 | 1,718 | 2,369 | -   | 26   | 57  | 13  | 94  | 12  | 56   | 1,710 | 6,100 | 11,400 | -   | 83  | 3,570 | 808 | 10,380 | 49  |
| Maximum (ppb) | 56   | 1,710 | 6,100 | 11,400 | -   | 83   | 3,570 | 808 | 10,380 | 49  | 10.4 | 122.0 | 600.0 | 500.0 | -   | 1.3 | 23.1 | 179.4 | 610.0 | 16.4 |
| Average (ppb) | 7    | 157 | 1,125 | 1,111 | -   | 2    | 115 | 33  | 1,569 | 3   | 10.4 | 122.0 | 600.0 | 500.0 | -   | 1.3 | 23.1 | 179.4 | 610.0 | 16.4 |
| Median of positive (ppb) | 23.8 | 161.5 | 1,350.0 | 1,000.0 | -   | 2.9  | 89.6 | 204.0 | 1,142.0 | 25.1 | 10.4 | 122.0 | 600.0 | 500.0 | -   | 1.3 | 23.1 | 179.4 | 610.0 | 16.4 |
| 1st quartile of positive (ppb) | 10.4 | 122.0 | 600.0 | 500.0 | -   | 1.3  | 23.1 | 179.4 | 610.0 | 16.4 | 10.4 | 122.0 | 600.0 | 500.0 | -   | 1.3 | 23.1 | 179.4 | 610.0 | 16.4 |
| 3rd quartile of positive (ppb) | 52.0 | 198.0 | 2,200.0 | 3,150.0 | -   | 5.5  | 164.8 | 283.0 | 2,087.5 | 32.2 | 52.0 | 198.0 | 2,200.0 | 3,150.0 | -   | 5.5 | 164.8 | 283.0 | 2,087.5 | 32.2 |
Table 11. Mycotoxin occurrence in finished feed samples surveyed in Northern, Central and Southern Europe.

| Finished Feed | Northern Europe | Central Europe | Southern Europe |
|---------------|-----------------|----------------|-----------------|
|                | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA |
| Number of tested samples | 1 | 27 | 27 | 1 | 1 | 45 | 489 | 579 | 65 | 95 | 66 | 72 | 104 | 48 | 51 |
| Positive (%) | 0 | 37 | 74 | 0 | 0 | 2 | 48 | 67 | 40 | 37 | 47 | 18 | 37 | 75 | 53 |
| Average of positive (ppb) | - | 87 | 641 | - | - | 1 | 118 | 792 | 327 | 4 | 6 | 72 | 431 | 2,007 | 2 |
| Maximum (ppb) | - | 339 | 1,889 | - | - | 1 | 1,045 | 25,759 | 2,282 | 30 | 103 | 165 | 1,252 | 7,008 | 17 |
| Average (ppb) | - | 32 | 475 | - | - | 0 | 56 | 533 | 131 | 2 | 3 | 13 | 158 | 1,505 | 1 |
| Median of positive (ppb) | - | 44.5 | 449.5 | - | - | 0.8 | 70.0 | 509.3 | 135.5 | 2.7 | 2.4 | 61.0 | 336.0 | 1,797.0 | 0.8 |
| 1st quartile of positive (ppb) | - | 41.0 | 203.3 | - | - | 0.8 | 34.0 | 269.3 | 60.1 | 1.3 | 1.2 | 40.0 | 224.5 | 554.0 | 0.7 |
| 3rd quartile of positive (ppb) | - | 65.3 | 914.5 | - | - | 0.8 | 117.0 | 917.0 | 341.5 | 6.0 | 4.2 | 88.0 | 515.3 | 3,040.3 | 1.0 |

Table 12. Mycotoxin occurrence in finished feed samples surveyed in North, South-East, South Asia and in Oceania.

| Finished Feed | North Asia | South-East Asia | South Asia | Oceania |
|---------------|------------|-----------------|------------|---------|
|                | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA | Afla | ZEN | DON | FUM | OTA |
| Number of tested samples | 622 | 661 | 671 | 604 | 575 | 465 | 454 | 447 | 465 | 448 | 127 | 120 | 111 | 123 | 122 | 75 | 86 | 86 | 74 | 74 |
| Positive (%) | 20 | 79 | 89 | 67 | 32 | 81 | 66 | 35 | 71 | 42 | 95 | 49 | 22 | 71 | 93 | 9 | 26 | 34 | 14 | 19 |
| Average of positive (ppb) | 24 | 271 | 829 | 1,542 | 4 | 29 | 53 | 287 | 800 | 3 | 95 | 51 | 156 | 438 | 23 | 5 | 291 | 296 | 1326 | 9 |
| Maximum (ppb) | 225 | 5,791 | 19,141 | 77,502 | 60 | 431 | 253 | 2,683 | 22,693 | 36 | 2,454 | 168 | 634 | 1,507 | 1,582 | 9 | 926 | 709 | 3,229 | 41 |
| Average (ppb) | 5 | 213 | 741 | 1,026 | 1 | 23 | 35 | 102 | 566 | 1 | 91 | 25 | 34 | 310 | 21 | 0 | 74 | 100 | 179 | 2 |
| Median of positive (ppb) | 11.0 | 106.0 | 513.5 | 806.0 | 2.0 | 13.0 | 41.0 | 143.5 | 570.0 | 1.5 | 49.0 | 40.0 | 128.0 | 336.0 | 4.0 | 3.0 | 128.0 | 224.0 | 1,283.0 | 5.2 |
| 1st quartile of positive (ppb) | 3.1 | 47.0 | 246.5 | 366.0 | 0.9 | 4.0 | 31.0 | 91.0 | 332.0 | 0.7 | 20.0 | 31.0 | 72.8 | 216.0 | 2.1 | 1.5 | 37.3 | 148.0 | 409.0 | 1.9 |
| 3rd quartile of positive (ppb) | 30.6 | 294.5 | 920.0 | 1,758.0 | 4.4 | 36.0 | 58.0 | 266.0 | 970.0 | 3.1 | 100 | 58.5 | 173.25 | 629 | 7.2 | 8.5 | 447.8 | 432.0 | 1,939.0 | 9.3 |
The corn contamination pattern differed between regions (Tables 2 and 3). Both in North America and in Central Europe the main contaminant of corn was shown to be DON (79% and 72% of positive samples, respectively), followed by FUM in both cases. Average contamination levels were quite similar for both regions (North America average of positive: 1085 ppb; Central Europe average of positive: 1421 ppb). In South America and southern Europe, the main contaminant observed in corn was FUM (92% and 90% of positive samples, respectively). Average contamination levels in both regions were different, with South American samples presenting higher values (average of positive: 3226 ppb) in comparison with Southern Europe (average of positive: 2271 ppb). The pattern followed in corn sourced in North Asia followed the same than that of North America and Central Europe with DON being the main contaminant (present in 92% of tested samples) at average levels of 1154 ppb. In Asia, in equatorial regions, the presence of Afla increased dramatically with 82% of positive samples for corn sourced in South Asia and 71% of positive samples for corn sourced in South-East Asia. Nonetheless, as the data show, the presence of fusariotoxins, such as FUM and DON, in these regions cannot be ignored. Corn samples sourced in Oceania presented quite high average levels of FUM (average of positive: 2823 ppb) present in 64% of analyzed samples.

In comparison with corn, soybean meal (SBM) appears to be less susceptible to mycotoxin contamination (Tables 4 and 5). In general, it can be said that mycotoxins such as ZEN and DON occur most frequently in this commodity throughout all regions. Surprisingly, one sample sourced in the USA presented a contamination level of 5500 ppb DON and another sample sourced in Turkey was positive for FUM with a contamination of 5088 ppb. This shows that even this commodity might unexpectedly present high contamination levels when conditions are favorable for mycotoxin production.

According to data presented in Tables 6–8, the major contaminant of wheat throughout all regions was DON. ZEN was also shown to be a main contaminant of this commodity, which is not a great surprise, as it is commonly known to co-occur with DON, a mycotoxin that shares the same producing fungi. In regards to positive samples, average levels for the American region (North and South America), Northern and Southern Europe and North Asia were around the 1000 ppb. In Central Europe, South-East Asia and Oceania, DON average levels were higher than that with 1534 ppb, 2251 ppb and 5046 ppb, respectively. A wheat sample from Austria was analyzed in October 2010 and showed a contamination of 49,000 ppb DON. Two distinct wheat samples from Australia were contaminated with 49,307 ppb DON and 23,278 ppb ZEN, the maximum levels found for this commodity worldwide. Both samples were analyzed in April 2011. Actually, the mycotoxin levels registered in both Austria in the year 2010 and Australia in the year 2011 were much higher than those reported for previous years [4]. As there is reason to believe that climate change can affect infection of crops with toxigenic fungi, the growth of these fungi and the production of mycotoxins [5], it is perhaps not erroneous to speculate that the occurrence of heavy rain and floods in both countries prior to crop harvest were responsible for such contamination levels.

In regards to Dried Distillers Grain with Solubles (DDGS), DON, ZEN and FUM were generally the main contaminants. Data shown in Table 9 reveals very high average levels for contaminated samples, especially for DON. These results reiterate those published in a previous report [6], thus confirming the need for monitoring the mycotoxin content of DDGS prior to its inclusion in animal diets.
Data shown in Tables 10–12 pertain to finished feeds (swine, poultry and dairy). The contamination pattern observed for each region can be related to that of the typically used main feedstuff. For example, in North American diets, corn is the main ingredient used, which explains to a great extent the prevalence of DON in these feeds. The same situation is observed in South America, where FUM is the main contaminant of corn, thus the major mycotoxin present in finished diets. In northern European countries, finished feeds typically have a higher proportion of cereals such as wheat, thus the matching pattern between wheat and finished feed sourced in this region. Besides this obvious but interesting conclusion, from an animal health and performance point of view, it is important to reiterate the fact that incredibly high maximum levels were found in finished feed samples sourced in all regions, but especially in Asia (2454 ppb Afla in South Asia, 5791 ppb ZEN, 19,141 ppb DON and 77,502 ppb FUM in North Asia and 1582 ppb OTA in South Asia). This draws attention to the fact that animals will frequently be faced with peak and fluctuating mycotoxin levels. Besides being well above regulated and recommended EU-values for the presence of mycotoxins in animal feed [7–9], the extremely high mycotoxin levels found will greatly impact performance and the health of animals ingesting them.

2.3. Co-occurrence of Mycotoxins

The simultaneous exposure of animals and poultry to more than one toxin is of concern and requires more study [10]. Synergistic effects may explain why animals sometimes respond negatively to mycotoxin levels much lower than those reported in scientific studies as able to cause mycotoxicoses.

From the 7049 samples, only 19% of them tested negative for the presence of the five analyzed mycotoxins. 33% showed the presence of one of them and two or more of the tested mycotoxins were present in 48% of the commodities.

Interestingly, when co-occurrence is evaluated in finished feed from different regions, differences are obvious. 10% of finished feeds in the Americas tested below the limit of detection for all analyzed mycotoxins, 50% tested positive for the presence of one mycotoxin, and in 40% of the samples, two or more mycotoxins were present. In Europe, 39% of the finished feed samples analyzed tested positive for 2 or more mycotoxins, 37% tested positive for one mycotoxin and 24% tested negative (below the limit of detection) for all five mycotoxins. In Asia, multi-mycotoxin contamination seems to be more prevalent, as 82% of the finished feed samples tested positive for the presence of two or more mycotoxins and 12% showed to be contaminated with one mycotoxin. Only 6% of the tested samples were found to be below the limits of detection.

3. Experimental Section

Between January 2009 and December 2011, a total of 7049 corn, soybean/soybean meal, wheat, dried distillers grains with solubles and finished feed samples were analyzed for the occurrence of aflatoxins, zearalenone, deoxynivalenol, fumonisins and ochratoxin A. The number of analyzed samples totaled 1653 in 2009, 2303 in 2010 and 3093 in 2011. Samples were sourced directly at animal farms or animal feed production sites from three major regions (Americas, Europe and Asia-Pacific). From the total number of samples analyzed throughout the 3 years, 2054 samples were
sourced in North (12.5%) and South (17.3%) America; 2151 samples were sourced in Europe (Northern: 1.5%; Central: 23.9%; Southern: 3.5%) and 2844 samples were sourced in Asia (North: 20.3%; South-East: 14.0%; South: 3.7% and Oceania: 3.3%). Samples from North America comprise those from the United States of America (only 1 sample originated in Canada was analyzed). 93% of the samples included in the South America group were sourced in Brazil with the remaining 7% originating from Argentina and Paraguay. European samples were sourced in the following countries: Norway, Sweden, Finland, Ireland and United Kingdom (Northern Europe); Austria, Belgium, Germany, France, the Netherlands, Hungary, Romania, Slovakia, Slovenia, Poland, Ukraine, Czech Republic, Croatia, Lithuania, Ukraine, Russia and Belorussia (Central Europe) and Greece, Italy, Portugal, Spain, Turkey and Serbia (Southern Europe). Samples in the group North Asia were sourced in China (83%), Japan, Korea and Taiwan. Malaysia, Philippines, Thailand, Vietnam and Indonesia comprised the South-East Asia group. Samples sourced in Sri Lanka, Pakistan, Bangladesh and India were grouped as South Asia and those from New Zealand and Australia in the Oceania group.

Analytical personnel and/or laboratory staff were not involved, and therefore were not able to influence any part of the sampling procedure. However, good sampling methods [11] were explained and sample providers were advised to follow them. Samples received in the lab weighed approximately 1 kg. After grinding the full lot sample, a subsample was taken for the actual analytical process. For dry and low-fat containing samples, such as various raw cereals, a ROMER Series II® subsampling mill (Romer Labs® Diagnostic GmbH, Tulln, Austria) was used. For all other commodities and ready-ground samples, kitchen blenders or other adequate instruments were used for homogenization. A choice could be made regarding the mycotoxins to be analyzed for, either “full toxin screen”, which covered aflatoxins (a sum of aflatoxin B1, aflatoxin B2, aflatoxin G1 and aflatoxin G2 content), zearalenone (ZEN), deoxynivalenol (DON), fumonisins (a sum of fumonisin B1 and fumonisin B2), and ochratoxin A (OTA), or analyses of selected mycotoxins. This explains why the number of analyzed mycotoxins in certain regions is sometimes different depending on the specific mycotoxin. The origin (name and location of submitter) of samples was kept strictly confidential; analytical certificates were submitted only to the originators of samples. Eighty percent of the samples were analyzed by high performance liquid chromatography (HPLC). Twenty percent of the samples were analyzed by Enzyme-Linked Immunosorbent Assay (ELISA), but only in North America and Europe where this option was available. Only single commodities were analyzed by ELISA. All analyses were done in fully accredited service labs. More complex matrixes that could interfere with the ELISA method, such as DDGS and finished feed, were analyzed by HPLC. Besides the nature of the samples, the geographical availability of analytical methods also explains the reason why certain feedstuffs were analyzed by ELISA rather than HPLC. Mycotoxin analyses were carried out as published by Rodrigues and Naehrer [4]. For the purpose of data analysis, non-detect levels are based on the detection limits (LOD) of the test method for each toxin (Table 13).
Table 13. Limit of detection of applied analytical methods.

|                  | HPLC | ELISA |
|------------------|------|-------|
| Afla (sum of AfB₁, AfB₂, AfG₁, AfG₂) | -    | 1     |
| AfB₁, AfB₂, AfG₁, AfG₂ | 0.3, 0.1, 0.1, 0.1 | -     |
| ZEN              | 10   | 40    |
| DON              | 50   | 250   |
| FB₁ and FB₂      | 25, 25 | -     |
| FUM (sum of FB₁ and FB₂) | -    | 250   |
| OTA             | 0.2  | 2     |

4. Conclusions

The results of this three-year mycotoxin survey reiterate the importance of mycotoxin testing prior to the feeding of animals. From the 23,781 mycotoxin analyses performed on the major five mycotoxins in terms of animal health and performance, 81% were positive for at least one mycotoxin. The presence of more than one mycotoxin in approximately half of the samples draws attention to the multi-mycotoxin contamination of feedstuffs and feeds and to the synergistic effects of mycotoxins in animals.

Moreover, it was shown that corn is a preferred substrate for fungal growth and mycotoxin production in comparison with soybean and wheat; however, seasons with abnormal weather conditions, such as excessive rain, have a great impact in contamination levels as shown with post-flooding wheat crops from Austria and Australia. DDGS continues to be a feedstuff which exhibits quite high contamination levels and for which careful screening prior to animal feeding is advised.

For further studies, it would be interesting to understand the importance of the so-called masked mycotoxins to the overall contamination of feedstuffs and feed; nonetheless, this might be difficult, as these compounds cannot be detected with conventional analytical procedures.

Conflict of Interest

The authors declare no conflict of interest.

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