

Article

Chemical Profile and Mycotoxin Analyses of Corn (Argentina, Brazil, and Ukraine), Soybean Meal (USA and Argentina), and Sunflower Meal (Ukraine) Used in Poultry Feed in Morocco

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Abstract

This study analyzes the nutritional quality and mycotoxin contamination of three key feed ingredients—corn, soybean meal (SBM), and sunflower meal (SFM)—imported into Morocco during the years 2019, 2020, and 2021. Samples were collected upon reception at the plant and analyzed in triplicate under standardized laboratory conditions. Chemical composition was evaluated using classical and NIR-based methods, while mycotoxin levels were assessed through ELISA and confirmed by HPLC. Corn samples from Argentina, Brazil, and Ukraine were assessed for their proximate composition and mycotoxin burden. While most nutritional parameters showed no significant differences between origins ($p > 0.05$), water activity (A_w) and digestible threonine content were significantly affected by origin ($p < 0.01$). Brazilian corn had the highest A_w (0.716), followed by Argentina (0.680), and Ukraine (0.662), a factor linked to its higher susceptibility to mold and mycotoxin development. Soybean meal from the U.S. and Argentina showed a general positive trend in favor of U.S. imports, with higher average crude protein (the CP content of American soybean meal was 46.912%, compared to 46.610% in Argentine soybean meal), fat, digestible lysine, and metabolizable energy. However, statistical differences were limited to water activity and moisture content ($p < 0.05$). American soybean meals are generally recognized for their consistent processing quality and superior amino acid digestibility. Sunflower meal, sourced exclusively from Ukraine, showed a steady improvement in crude protein (from 35.97% in 2019 to 36.99% in 2021) and metabolizable energy, alongside reduced crude fiber content, enhancing its nutritional value in poultry diets. The consistent use of Ukrainian SFM in Morocco reflects both supply stability and quality. Regarding mycotoxins, origin had a significant effect on several compounds. Argentine and Brazilian corn showed higher mean levels of fumonisins (1165.26 and 1019.52 ppb), ochratoxin A (2.26 and 3.02 ppb), and zearalenone (36.99 and 21.92 ppb) compared to Ukrainian corn, which consistently had the lowest levels across all major mycotoxins (e.g., fumonisins = 200 ppb; zearalenone = 4.90 ppb). Aflatoxin B1 levels remained constant at 0.2 ppb across all origins. These findings confirm the influence of geographic origin—particularly water activity—on mycotoxin risk in imported maize.



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1. Introduction

Corn, soybean meal (SBM), and sunflower meal (SFM) are among the most important raw materials in poultry and livestock feed formulations, providing essential energy and protein sources [1]. However, their chemical profiles vary considerably depending on geographical origin, agronomic conditions, and processing methods.

Corn composition shows notable differences in crude protein (CP), ether extract (EE), gross energy (GE), and mineral content. Comparative studies across countries have reported CP values ranging from 7.12% in Brazil to 7.60% in China, EE from 3.30% (USA) to 3.87% (Brazil), and GE values between 3836 and 3995 kcal/kg, with the highest values found in Brazilian corn [2]. Such differences are influenced by variety, soil fertility, climate, and environmental stress factors [2].

Similarly, the nutritional value of soybean meal differs according to its origin. A large-scale near-infrared spectroscopy (NIRS) analysis of 77,478 SBM samples collected from 2018 to 2021 showed that Argentine SBM generally had the lowest CP, EE, and fiber contents, whereas Brazilian SBM had the highest CP, EE, fiber, and digestible lysine values. U.S. SBM, in contrast, showed the highest metabolizable energy (ME, MEN) and amino acid digestibility [3]. Meta-analysis results support these findings, indicating significant differences between Brazilian, Argentine, U.S., and Indian SBM in terms of CP, fiber, sugars, iron, and essential amino acids such as lysine, methionine, threonine, and cysteine [3].

Sunflower meal composition is also highly variable, particularly depending on the proportion of hulls remaining after processing. Standard SFM typically contains 30–34% CP, 20–25% crude fiber, and 8–10% lignin, which limits its value for poultry and swine due to its high fiber content [4]. However, dehulled sunflower meal (HiSFM) can reach ~46% CP and reduced fiber content (8–14%), demonstrating the impact of both raw material origin (seed hull content) and processing technology on its chemical profile [5].

The objective of this study is to present the average values of the chemical characteristics, key nutrients, and antinutritional factors of three major feed ingredients—corn, soybean meal, and sunflower meal—sourced from different regions of the world over the three years 2019, 2020, and 2021. Mycotoxin analyses were conducted on the maize batches to complement the study. Specifically, ELISA assays were performed, with results cross-validated using the HPLC method for quality control. It is hypothesized that the nutritional values of these ingredients vary according to their geographical origin, and that the choice of origin represents a critical nutritional factor in the formulation of compound feeds for poultry and livestock.

2. Materials and Methods

2.1. Experimental Protocol

Table 1 presents the imports of the main raw materials used in the formulation of compound feeds for poultry and livestock at the BENWAY feed manufacturing plant. The data cover the years 2019, 2020, and 2021, highlighting three key raw materials: corn, soybean meal (SBM), and sunflower meal (SFM). For each product, the table provides information on the country of origin, the number of analyzed samples representing the received batches, and the annual imported tonnage. These are essential data for assessing traceability, quality, and associated health risks.

All samples were analyzed in triplicate under identical laboratory conditions. Sampling was carried out upon reception of the batches, prior to storage at the plant.

In 2020, the total imported volumes of raw materials intended for animal feed—particularly corn, soybean meal, and sunflower meal—experienced a marked decline. This reduction is largely attributed to global logistical disruptions linked to the COVID-19 pandemic, which severely impacted international supply chains [6].

Table 1. Samples taken for chemical analyses.

Raw Material	Year	Origin	Number of Samples = Number of Lots	Annual Tonnage (Metric ton (1000 kg))
Corn	2019	Argentina	99	39,026
Corn	2019	Brazil	48	3900
Corn	2019	Ukraine	6	300
Soybean meal	2019	USA	65	11,674
Soybean meal	2019	Argentina	15	2375
Sunflower meal	2019	Ukraine	73	7130
Corn	2020	Argentina	17	9400
Corn	2020	Ukraine	6	2000
Soybean meal	2020	USA	8	3200
Sunflower meal	2020	Ukraine	21	3550
Corn	2021	Argentina	49	44,000
Corn	2021	Brazil	3	3000
Soybean meal	2021	USA	41	6920
Soybean meal	2021	Argentina	5	4130
Sunflower meal	2021	Ukraine	34	7552

2.2. Chemical Analyses Performed on the Samples

The following parameters were determined as part of the chemical analysis of the samples: moisture content, water activity, crude protein content, crude fat content, crude fiber content, ash content (mineral matter), starch content (for corn), protein dispersibility index (PDI), digestible protein content in KOH, reactive lysine content, ratio of reactive lysine to total lysine, PCI index (to assess soybean meal batches), urease activity (mg N/g/min), and protein solubility in potassium hydroxide (KOH).

Additional nutritional parameters were predicted using the calibration equations from the NIR device database (EVONIK calibration): poultry metabolizable energy, digestible lysine, digestible methionine + cystine, and digestible threonine.

Two analytical methods were employed for the analysis of mycotoxins: ELISA (Enzyme-Linked Immunosorbent Assay) as the primary screening method using Romer Labs kits, and HPLC (High-Performance Liquid Chromatography) for confirmation and verification purposes. An ELISA was applied for the initial quantification of mycotoxin levels due to its efficiency and suitability for large sample screening. A subset of samples was subsequently analyzed using HPLC to verify ELISA results and ensure accuracy and reliability through cross-validation.

2.3. Sampling

For each received batch, a representative sample was analyzed. The sampling procedure was as follows:

Three sampling points were obtained from each truck (with a capacity of 14 metric tons).

- Ten trucks per batch were randomly selected for corn sampling.
- Six trucks per batch were randomly selected for soybean meal and sunflower meal sampling.
- Three samples were obtained from each truck: the front, middle, and rear, using a deep sampling probe.

2.4. Sample Preparation

For each batch, around twenty trucks deliver the raw materials, with arrivals usually spread over 3 to 5 days. The trucks are randomly selected according to the required number of samples, the designated sampling points, and the standardized sampling method. The

collected samples are then stored in sealed containers to preserve their nutritional value and moisture content until all samples are obtained. Subsequently, the samples are pooled and divided using a sample divider to obtain one representative sample per batch for each raw material.

For each batch, sampling was carried out using three probe collections of 500 g each, resulting in a total of 1.5 kg per truck. For corn, this protocol was applied to 10 trucks, yielding a composite sample of 15 kg per corn batch. For soybean meal and sunflower meal, the total sampled quantity per batch was 9 kg for each raw material (Figure 1).

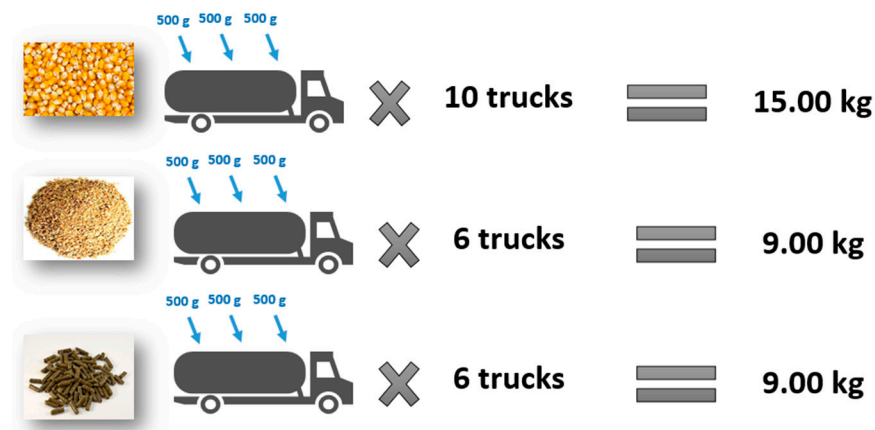


Figure 1. Sampling protocol for the three raw materials.

The selection of trucks was performed randomly, in accordance with the sampling protocol established for the three raw materials studied, and applied to all batches.

The individual sub-samples were homogenized to obtain a single composite sample per batch and per raw material. These composite samples were then processed using a sample divider (Figure 2) to produce equal fractions, allowing for the collection of a final representative sample intended for analysis.



Figure 2. Sample divider used to split bulk samples into representative subsamples.

The principle of a sample divider is to reduce the size of a bulk sample into several representative subsamples, ensuring that each subsample retains the chemical and physical properties of the original material.

Before analysis, all samples underwent homogeneous grinding. This grinding step is essential both for conducting reference chemical analyses, including mycotoxin quantification and for nutritional predictions using near-infrared spectroscopy (NIR), particularly for poultry metabolizable energy (MEp) values and digestible amino acid contents.

2.5. Chemical Analysis Procedures Conducted at the Plant Laboratory

Table 2 shows the analytical methods performed and equipment.

Table 2. Analytical methods performed and equipment.

Nutrient	Analytical Method	Equipment	Origin of the Main Equipment
Representativity of the samples		Sample divider	PFEUFFER made in Germany
Crude Protein	Determination of protein content by the Kjeldahl method	Ball mill ZM 200, KJELDATHERM 8-station mineralizer with 8 tubes for mineralization; VAPODEST 400 automatic distillation unit without titration; analytical balance with 0.1 mg precision; nitrogen-free paper; adjustable sulfuric acid dispenser; automatic stirrer; magnetic stir bar; 250 mL narrow-neck Erlenmeyer flasks and glass beakers, analytical Balance.	Ball mill; RETSCH, Germany KJELDATHERM, VAPODEST 400 Gerhardt Analytical Systems, Germany analytical Balance; BEL Engineering made in Italy
Moisture	Determination of moisture content (%) by drying oven	Thermal balance (drying oven); metal drying dishes.	Thermal balance VIBRA made in Japan
Ash (Mineral Matter)	Determination of ash content by incineration	Digital ventilated muffle furnace; analytical balance; numbered quartz crucibles; silica gel; glass desiccator. analytical Balance	Nabertherm made in Germany
Water Activity (Aw)	Determination of water activity using an A-W meter	A-W meter; sample cups.	Aqualab
Crude Fat	Extraction by Soxhlet method	Soxhlet extractor; boiling flask; condenser; solvent (hexane or ether); analytical balance; desiccator.	400 Gerhardt Analytical Systems, made in Germany
Starch	Enzymatic or acid hydrolysis followed by colorimetric assay	Water bath or incubator; enzymes (α -amylase, amyloglucosidase); UV-visible spectrophotometer; glassware; analytical balance.	400 Gerhardt Analytical Systems, made in Germany
Protein Dispersibility Index (PDI/IDP)	Determination of protein solubility in water at 24 °C with agitation for 10 min (AOCS Ba 10–65 method)	High-speed agitator Rotofix 32 A; 0.106 mm sieve; beakers; analytical balance; centrifuge; pipettes.	HETTICH
Poultry Metabolizable Energy	Near-infrared spectroscopy (NIR)	NIR device; analytical balance.	EVONIK calibration
Digestible Amino Acids	Near-infrared spectroscopy (NIR)	NIR device; analytical balance.	EVONIK calibration
Mycotoxins	ELISA/HPLC	ELISA (Enzyme-Linked Immunosorbent Assay) as the primary screening method using Romer Labs kits, and HPLC (High-Performance Liquid Chromatography) for confirmation and verification purposes	Romer Labs, made in USA Agilent Technologies, made in USA

2.6. Statistical Analysis

Due to the violation of normality assumptions required for parametric tests (such as ANOVA or Student's *t*-test), non-parametric statistical methods were employed to ensure the validity and robustness of the comparative analyses. The Kruskal–Wallis H test was used to assess differences between more than two independent groups, while the Mann–Whitney U test was applied for comparisons between two groups. This approach was selected to accommodate non-normal data distributions and unequal sample sizes, particularly noting the small sample size in group 3 (number of batches analyzed $n = 9$), which could otherwise compromise the statistical power of parametric tests. Although some variables (e.g., starch content) showed normal distributions, the Kruskal–Wallis test was uniformly applied across all variables to maintain methodological consistency. A

significance level of $p < 0.05$ was considered statistically significant. All analyses were performed using appropriate statistical software SPSS V26.

Since the Shapiro–Wilk and Kolmogorov–Smirnov normality tests indicated that all mycotoxin concentration data deviated significantly from a normal distribution ($p < 0.05$ for almost all origins and compounds), the assumptions required for a parametric one-way ANOVA were not met. Consequently, non-parametric tests were applied: the Kruskal–Wallis test was used to compare the three origins (Argentina, Brazil, and Ukraine) for each year, and the Mann–Whitney U test was employed for pairwise post hoc comparisons

3. Results

3.1. Chemical Composition of Corn Imported from Argentina, Brazil, and Ukraine to Morocco in 2019–2021 by a Compound Feed Manufacturing Plant for Poultry

3.1.1. Moisture Content (H₂O%) and Water Activity (Aw) in Corn

Moisture content values ranged from 12.625% to 14.583%, while water activity (Aw) varied between 0.677 and 0.747. The highest moisture content was observed in Brazilian corn from 2021 (14.583%), which also showed one of the highest water activity values (0.721). (The detailed chemical composition of corn from the three origins over the three years is presented in Appendix A, Tables A1–A7).

Water activity (Aw), which is closely linked to the availability of free water for microorganisms, remained around 0.68–0.69.

3.1.2. Crude Protein (CP%) and Digestible Amino Acids in Corn

Crude protein (CP) content in corn samples ranged from 7.013% (Brazil, 2021) to 7.483% (Brazil, 2019). These values comply with established standards for corn grain [7,8]. Digestible lysine values were relatively consistent across origins and years, varying from 0.218% to 0.224%, while digestible methionine + cysteine ranged from 0.299% to 0.313%. Digestible threonine content showed more noticeable variation, with Brazilian corn in 2019 presenting the highest value (0.253%). Post hoc Mann–Whitney analysis indicated that Brazilian maize exhibited a significantly higher digestible threonine content compared with other origin

3.1.3. Starch Content (%) and Metabolizable Energy (ME) in Corn

Starch is the main energy source in corn. Its content was high and stable:

- Corn AR (Argentina): 64.03%
- Corn Ukrainien (Ukraine): 64.07%
- Corn Brésilien (Brazil): 63.80%

Metabolizable energy (ME) values ranged from 3318.000 kcal/kg (Argentina, 2020) to 3352.200 kcal/kg (Brazil, 2019), while starch content varied between 63.800% (Argentina, 2019; Brazil, 2019) and 64.207% (Argentina, 2021).

3.1.4. Crude Fat (CF%), Crude Fiber (CFb%), and Ash (MM%) in Corn

Crude fat content in the analyzed corn samples ranged from 3.929% (Argentina, 2020) to 4.167% (Ukraine, 2019), while crude fiber varied between 1.850% (Argentina, 2020) and 2.133% (Ukraine, 2019). Ash content showed a narrower range, from 1.090% (Ukraine, 2020) to 1.267% (Brazil, 2021). The relatively higher fat levels in Ukrainian corn from 2019 may have contributed to its metabolizable energy value, whereas variations in fiber content could partially explain differences in energy availability among samples. The ash values indicate minor differences in mineral content across origins and years, although slight variations were observed between origins and years, statistical analysis indicated that these differences were not significant for the three origins studied

3.1.5. Nutritional Variability of Corn by Origin

Moisture Content

Argentine corn showed the highest variability in moisture (CV = 6.35%), followed by Brazilian corn (4.47%), while Ukrainian corn exhibited the lowest variability (2.82%). This suggests that Argentine corn batches were less homogeneous in terms of moisture, likely reflecting differences in harvesting, storage, or transport conditions.

Water Activity (Aw)

The greatest variability was observed in Argentine corn (CV = 7.16%), indicating substantial heterogeneity in preservation conditions. Brazilian corn showed moderate variability (2.82%), whereas Ukrainian corn was highly homogeneous (0.26%), suggesting greater stability in this parameter.

Starch Content

Coefficients of variation were low across all origins (1.95% for Argentina, 0.91% for Brazil, and 1.36% for Ukraine), indicating that starch levels were relatively consistent among batches regardless of origin. This was expected, as starch is a major and relatively stable component of corn.

Variability was mainly observed in moisture and particularly in water activity, especially in Argentine corn, which may affect storage quality and increase the risk of fungal growth and mycotoxin development. In contrast, major nutritional components such as starch remained relatively stable across batches and origins.

3.2. Kruskal–Wallis Test for Comparing the Corn Origins (2019–2021)

Kruskal–Wallis tests (Table 3) were conducted for all measured variables to assess differences between maize samples from three different origins over the years 2019, 2020, and 2021. Variables such as moisture (%), crude protein (%), crude fat (%), crude fiber (%), ash (%), metabolizable energy (kcal/kg), digestible lysine (%), and starch (%) showed no significant effect of origin ($p > 0.05$), indicating comparable values across Argentina, Brazil, and Ukraine.

Table 3. The effect of origin on the chemical composition of corn imported over three years.

Parameter	H (Kruskal–Wallis)	df	p-Value	Post Hoc Mann–Whitney	Interpretation
Moisture (%)	1.799	2	0.407	–	No significant difference between origins.
Water Activity (Aw)	19.539	2	0.000	Ar vs. Br: $p = 0.000$ (significant) Origin Ar vs. Uk: $p = 0.102$ (ns) Origin Br vs. Uk: $p = 0.889$ (ns)	Significant difference due to Argentina vs. Brazil.
Crude Protein (%)	2.604	2	0.272	–	No significant difference.
Crude Fat (%)	0.666	2	0.717	–	No significant difference.
Crude Fiber (%)	2.807	2	0.246	–	No significant difference.
Ash (%)	2.259	2	0.323	–	No significant difference.
Starch (%)	0.143	2	0.931	–	No significant difference.
Metabolizable Energy (kcal/kg)	4.419	2	0.110	–	No significant difference.
Digestible Lysine (%)	0.394	2	0.821	–	No significant difference.
Digestible Methionine + Cysteine (%)	5.684	2	0.058	–	Trend toward difference, not significant.
Digestible Threonine (%)	15.118	2	0.001	Origin Ar vs. Br: $p = 0.000$ (significant) Origin Ar vs. Uk: $p = 0.419$ (non significant) Origin Br vs. Uk: $p = 0.009$ (significant)	Brazilian maize showed a significantly higher digestible threonine content

Mann–Whitney post hoc comparisons use Bonferroni correction: $\alpha = 0.05/3 \approx 0.017$. “ns” = not significant.

For water activity (A_w), the Kruskal–Wallis test revealed a significant overall difference between origins ($H = 19.539$; $p = 0.000$). Post hoc pairwise comparisons using Mann–Whitney tests with Bonferroni correction indicated that this difference was driven exclusively by the comparison between Argentinian and Brazilian maize ($p < 0.017$), while the other pairs did not show significant differences. Argentinian maize had an average water activity of 0.680, compared to 0.716 for Brazilian maize, making it the most at risk for mold development and potential mycotoxin contamination. Argentine corn presented the lowest average water activity value (0.68), indicating better preservation of its nutritional quality during storage. Overall, the origin factor appears to have a limited impact on corn composition over the three years studied, with water activity being the most sensitive parameter.

Similarly, Digestible Threonine (%) showed a significant difference between origins ($H = 15.118$; $p = 0.001$). Post hoc Mann–Whitney tests demonstrated that two pairs of origins had significant differences after Bonferroni correction, contributing to the overall Kruskal–Wallis result. Brazilian maize showed a significantly higher digestible threonine content, with an average value of 0.253%, which is the highest among all the maize origins studied.

For digestible methionine + cysteine (%), a trend toward significance was observed ($H = 5.684$; $p = 0.058$), suggesting that some origins may have slightly different values, but this difference is not statistically significant at the 5% level.

In summary, only water activity (A_w) and digestible threonine (%) showed significant differences between maize origins, Digestible methionine + cysteine (%) showed a trend toward variation, and all other variables were comparable across Argentina, Brazil, and Ukraine.

3.3. Chemical Composition of Soybean Meal Imported from the USA and Argentina to Morocco in 2019–2021 by a Poultry Compound Feed Manufacturing Plant

3.3.1. Analysis Results of Soybean Meal Imported from the USA

The imported soybean meal from the USA showed a moisture content of 11.22% and water activity (A_w) of 0.658. Crude protein was 46.91%, with 2.35% crude fat, 3.66% crude fiber, and 6.24% ash. Starch content was low at 0.71%, while metabolizable energy (MEp) was 2369.73 kcal/kg. Digestible amino acids were 2.56% lysine, 1.10% methionine + cysteine, and 1.51% threonine. Protein quality indicators were high, with PDI at 11.89%, urease activity of 0.045 mg N/g/min, and protein solubility in KOH at 76.91%, indicating good nutritional quality for poultry feed (the detailed chemical composition of soybean meal imported from the USA is presented in Appendix A, Tables A8–A10).

3.3.2. Results of the Analysis of Soybean Meal Imported from Argentina

The soybean meal imported from Argentina exhibited a moisture content of 10.85% and water activity (A_w) of 0.647. Crude protein was high at 46.61%, with 2.08% crude fat, 3.67% crude fiber, and 6.55% ash. Starch content was low (0.72%), and metabolizable energy (MEp) was 2365.83 kcal/kg. Digestible amino acids included 2.55% lysine, 1.11% methionine + cysteine, and 1.53% threonine. Protein quality indicators were strong, with a PDI of 11.91%, urease activity of 0.042 mg N/g/min, and protein solubility in KOH of 80.38%. Notably, the Argentine soybean meal showed larger standard deviations for most parameters compared with the USA soybean meal, which may affect the consistency and stability of the Argentine product. (The detailed chemical composition of soybean meal imported from Argentina is presented in Appendix A, Tables A11 and A12).

3.3.3. Comparison of the Quality of Soybean Meal Imported from the United States and Argentina (2019–2021)

Crude Protein and Stability of Protein Content

Both origins show satisfactory crude protein (CP) levels (46–47%), but American soybean meal stands out for its year-to-year consistency (Tables A11–A15):

CP USA: 47.26% (2019), 46.43% (2020), 46.82% (2021)

CP Argentina: 46.76% (2019), 46.46% (2021), with a minimum observed at 43.60%

Digestible Amino Acid Profile

American soybean meal shows excellent digestibility for essential amino acids, key indicators in monogastric nutrition:

Digestible Lysine USA: 2.58% (2019), 2.54% (2021)

Digestible Methionine + Cystine: 1.11% (2019), 1.08% (2021)

Digestible Threonine: 1.52–1.50%

Thermal Processing Control

Processing quality is critical to preserving protein digestibility and neutralizing anti-nutritional factors. American soybean meal shows exemplary thermal processing indicators: IDP: controlled (11.01–12.76%), versus 10.74–12.23% for Argentine meal, urease activity: very low (0.05 mg N/g/min in 2019), similar to Argentina (0.04), KOH protein solubility: 75–78% in the USA, versus 77.85–82.90% in Argentina higher values sometimes indicating overcooking risk [9]. The optimum PDI range for monogastric feeds is generally between 15 and 25%, guaranteeing good protein digestibility while ensuring the inactivation of anti-nutritional compounds [10].

Reactive lysine/total lysine (USA 2021): 89.37%, indicating minimal thermal degradation of amino acids. These values show optimal heat treatment for American soybean meal, neither undercooked nor overcooked, promoting protein bioavailability.

Metabolizable Energy (ME) and Overall Digestibility

ME USA: between 2348 and 2390 kcal/kg

ME Argentina: average 2365 kcal/kg (more variability observed). Equivalent values, but with more homogeneous energy values for American soybean meal, useful for precise feed formulation.

While Argentine soybean meal remains acceptable, it shows greater batch-to-batch variability, which may lead to performance variations and requires greater attention in feed formulation.

3.3.4. Statistical Comparison Between U.S. and Argentine Soybean Meal (Mann–Whitney U Test)

This analysis evaluates whether there are statistically significant differences between two origins of soybean meal across various nutritional and quality parameters. The Mann–Whitney U test (non-parametric test for two independent samples) was applied. A significance threshold of $p < 0.05$ was used.

The moisture content in American soybean meal is significantly higher than that of Argentine soybean meal ($p < 0.05$) (Table 4).

Among the parameters analyzed, only moisture and water activity showed statistically significant differences between the two soybean meal origins, with the U.S. samples generally showing slightly higher values. All other parameters—including protein content, digestible amino acids, urease activity, and protein solubility—did not differ significantly between the two sources.

Table 4. Comparison between American and Argentine soybean meal.

	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-Tailed)
Moisture (%)	589.000	779.000	−2.750	0.006
Water Activity (Aw)	149.000	204.000	−2.004	0.045
Crude Protein (%)	760.000	970.000	−1.635	0.102
Crude Fat (%)	114.000	150.000	−1.577	0.115
Crude Fiber (%)	112.000	1015.000	−0.441	0.659
Ash (%)	763.000	6119.000	−1.524	0.127
Starch (%)	85.000	865.000	−1.084	0.278
Metabolizable Energy (kcal/kg)	85.000	106.000	−0.827	0.408
Digestible Lysine (%)	90.500	111.500	−0.629	0.529
Digestible Methionine + Cysteine (%)	59.500	725.500	−1.744	0.081
Digestible Threonine (%)	65.000	731.000	−1.547	0.122
Protein Dispersibility Index (PDI. %)	243.500	298.500	−0.316	0.752
Urease Activity (mg N/g/min)	3.000	6.000	0.000	1.000
Protein Solubility in KOH (%)	155.500	1145.500	−1.007	0.314

3.3.5. Comparative Variability of American and Argentine Soybean Meals

The American soybean meal exhibited a coefficient of variation in moisture content of 8.65% in 2019 compared to 4.35% in 2021. Similarly, the Argentine soybean meal showed a high coefficient of variation in 2019 (9.45%) versus 2.23% in 2021. Crude protein content did not display considerable variability between batches, with the American soybean meal presenting a CV of 2.15% in 2019 and the Argentine soybean meal 2.73% in the same year. In contrast, higher variability between batches was observed in secondary parameters such as crude fat (27.13% for American soybean meal in 2019 and 30.78% for Argentine soybean meal in 2019) and starch (26.46% for American soybean meal in 2019 and 10.50% for Argentine soybean meal in 2019). The protein dispersibility index (PDI) also exhibited marked variability between batches, particularly in Argentine soybean meal (15.82% in 2019) compared to American soybean meal (12.05% in 2019).

3.4. Chemical Composition of Sunflower Meal Mainly Imported from Ukraine to Morocco in 2019–2021 by a Poultry Feed Manufacturing Plant

Sunflower meal constitutes a partial alternative to soybean meal in poultry feed formulations, notably due to its availability and more competitive cost. However, its high fiber content and less balanced amino acid profile compared to soybean limit its inclusion in fast-growing poultry diets.

Ukrainian sunflower meal is the primary source used in the poultry industry in Morocco, which explains why the factory does not import sunflower meal from any other origin. An analysis of its chemical composition over the years 2019, 2020, and 2021 shows a notable evolution in its nutritional characteristics. The crude protein (CP) content steadily increased from 35.97% in 2019 to 36.99% in 2021, reflecting an improvement in its nutritional value. Similarly, the metabolizable energy (MEp) rose from 1553.61 kcal/kg to 1600.17 kcal/kg, which is beneficial for poultry feed efficiency. Crude fiber content decreased from 17.97% to 17.03%, enhancing digestibility. Meanwhile, ash content showed slight fluctuations, reaching 6.79% in 2021. Regarding digestible amino acids, digestible methionine + cysteine showed a slight increase from 1.17% to 1.23%, while digestible

lysine and digestible threonine remained relatively stable across the three years. (The detailed chemical composition of sunflower meal imported from Ukraine is presented in Appendix A, Tables A13–A15).

A Kruskal–Wallis H test was conducted to determine whether there were statistically significant differences in the chemical composition of sunflower meal across three years ($df = 2$). The results are shown in Table 5.

Table 5. The chemical composition of sunflower meal across three years.

	Kruskal-Wallis H	df	Asymp. Sig.	Interpretation
Moisture (%)	10.004	2	0.007	Significant effect of year
Water Activity (A_w)	1.500	2	0.472	No significant effect
Crude Protein (%)	9.651	2	0.008	Significant effect
Crude Fat (%)	6.399	2	0.041	Significant effect
Crude Fiber (%)	3.882	2	0.144	No significant effect
Ash (%)	20.967	2	0.000	Highly significant effect
Metabolizable Energy (kcal/kg)	9.780	2	0.008	Significant effect
Digestible Lysine (%)	5.503	2	0.064	Not statistically significant (close)
Digestible Methionine + Cysteine (%)	8.327	2	0.016	Significant effect
Digestible Threonine (%)	1.307	2	0.520	No significant effect

The results indicate that the year has a statistically significant effect on several key nutritional parameters of sunflower meal, including the following:

- Moisture;
- Crude protein;
- Crude fat;
- Ash;
- Metabolizable energy
- Digestible methionine + cysteine.

No significant year-to-year variation was found for water activity, crude fiber, digestible lysine (borderline), and digestible threonine.

4. Mycotoxin Profiling of Maize Batches Analyzed in This Study

The assessment of mycotoxin contamination in imported corn revealed substantial variations among origins. For deoxynivalenol (DON), Brazilian corn exhibited the highest mean concentration (1354.44 ppb; range: 200–3980 ppb), followed by Argentine corn (752.81 ppb; 270–3300 ppb) and Ukrainian corn (456.00 ppb; 410–560 ppb). Fumonisin (B1 + B2) were most elevated in Argentine corn (1165.26 ppb; 210–6040 ppb), with Brazilian corn showing slightly lower levels (1019.52 ppb; 280–2120 ppb) and Ukrainian corn presenting the lowest and constant value (200 ppb). Ochratoxin A (OTA) concentrations were highest in Brazilian corn (3.02 ppb; 1.9–7.15 ppb), while Argentine and Ukrainian corn showed lower means of 2.26 ppb (1–6.22 ppb) and 1.90 ppb (constant), respectively. T-2 toxin levels were highest in Argentine corn (13.91 ppb; 10–71.34 ppb) compared to Brazilian (10.00 ppb) and Ukrainian corn (10.05 ppb). Zearalenone contamination was markedly higher in Argentine corn (36.99 ppb; 0–199.25 ppb), followed by Brazilian (21.92 ppb; 2.62–61.75 ppb) and Ukrainian corn (4.90 ppb; 3.10–6.86 ppb). In contrast, aflatoxin B1 concentrations were low and uniform across all origins (0.20 ppb).

Effect of Corn Origin on Mycotoxin Profile

An overview of the contamination by the six mycotoxins across the different corn origins is presented in detail in Appendix A, Table A19.

The mycotoxin contamination profile of maize varied according to its origin (Argentina, Brazil, and Ukraine), as demonstrated by both descriptive statistics and the Kruskal–Wallis H test.

Fumonisin B1 + B2 showed significant differences among origins ($H = 6.145$, $p = 0.046$), with Argentine corn exhibiting the highest mean level (1165.26 ppb), followed closely by Brazilian corn (1019.52 ppb). Ukrainian corn showed minimal contamination, with a consistent value of 200 ppb across all samples.

Ochratoxin A also varied significantly ($H = 8.230$, $p = 0.016$), with Brazilian corn displaying the highest average (3.02 ppb) and Ukrainian corn the lowest (1.90 ppb).

A significant difference was also observed for T-2 toxin ($H = 6.624$, $p = 0.036$), where Argentine corn had a notably high mean (13.91 ppb), in contrast to the low and consistent levels in Brazilian and Ukrainian corn (around 10 ppb).

Similarly, zearalenone levels significantly differed across origins ($H = 6.772$, $p = 0.034$), with Argentine corn again showing the highest mean value (36.99 ppb), followed by Brazilian (21.92 ppb), and Ukrainian corn presenting the lowest average (4.90 ppb).

In contrast, deoxynivalenol (DON) levels did not significantly differ by origin ($H = 1.683$, $p = 0.431$), despite Brazilian corn showing the highest mean (1354.44 ppb) and Ukrainian corn the lowest (456.00 ppb).

Aflatoxin B1 levels were identical across all samples (0.2 ppb), with no statistical difference ($H = 0.000$, $p = 1.000$), indicating uniform and minimal contamination.

These results confirm that maize origin significantly affects contamination levels for several mycotoxins, particularly fumonisins, ochratoxin A, T-2 toxin, and zearalenone, while DON and aflatoxin B1 remained statistically similar between sources. Ukrainian maize consistently showed the lowest mycotoxin burden, making it the least contaminated among the three origins analyzed (Table 6).

Table 6. Effect of maize origin on mycotoxin contamination: A Kruskal–Wallis H test approach.

	Deoxynivalenol DON (ppb)	Fumonisin B1 + B2 (ppb)	Ochratoxin (ppb)	Toxins T-2 (ppb)	Zéaralenone (ppb)	Aflatoxine B1 (ppb)
Kruskal–Wallis H	1.683	6.145	8.230	6.624	6.772	0.000
df	2	2	2	2	2	2
Asymp. Sig.	0.431	0.046	0.016	0.036	0.034	1.000

5. Discussion

5.1. Chemical Profile of Corn Imported from Argentina, Brazil, and Ukraine to Morocco in 2019–2021 by a Compound Feed Manufacturing Plant for Poultry

5.1.1. Analysis of Moisture Content ($H_2O\%$) and Water Activity (A_w) in Corn

The highest moisture content was observed in Brazilian corn from 2021 (14.583%), which also showed one of the highest water activity values (0.721). Such elevated values may increase the risk of fungal growth and mycotoxin production during storage, particularly when exceeding the generally recommended thresholds for safe grain conservation [11].

Water activity (A_w), which is closely linked to the availability of free water for microorganisms, remained around 0.68–0.69. While these values are acceptable, they are close to the critical threshold of 0.70, beyond which mold growth—such as *Aspergillus* spp.—becomes possible [12]. Regular monitoring of mycotoxin contamination is therefore recommended.

5.1.2. Analysis of Crude Protein (CP%) and Digestible Amino Acids in Corn

Crude protein (CP) content in corn samples ranged from 7.013% to 7.483%.

These values are typical of corn but relatively low compared to poultry nutritional requirements. This confirms the necessity of systematically supplementing formulas with protein-rich sources (such as soybean meal and synthetic amino acids) [13].

5.1.3. Analysis of Starch Content (%) and Metabolizable Energy (ME) in Corn

The values fall within the optimal range (60–70% of dry matter), ensuring good digestibility and an appropriate energy supply for poultry. The moderate standard deviation (~1–1.5) reflects consistent quality.

In general, higher starch levels tended to correspond to higher ME values, although exceptions were observed, suggesting that factors such as protein, fat, and fiber composition may also influence ME. Brazilian corn from 2019 showed the highest ME value despite having one of the lowest starch contents, indicating that other nutritional components likely contributed to its energy value.

The mean (2019, 2020, and 2021) metabolizable energy (ME) values followed the same trend: corn from Argentina: 3331.06 kcal, corn from Brazil: 3352.20 kcal, and corn from Ukraine: 3343.67 kcal.

The values of EMP values align with [14] recommendations and are suitable for formulating grower and finisher diets for broiler chickens.

5.1.4. Analysis of Crude Fat (CF%), Crude Fiber (CFb%), and Ash (MM%) in Corn

The relatively higher fat levels in Ukrainian corn from 2019 may have contributed to its metabolizable energy value, whereas variations in fiber content could partially explain differences in energy availability among samples. The ash values indicate minor differences in mineral content across origins and years.

5.2. Chemical Composition of Soybean Meal Imported from the USA and Argentina to Morocco in 2019–2021

A general positive trend was observed in American soybean meal, which exhibited higher average levels of crude protein, crude fat, metabolizable energy for poultry, and digestible lysine compared to Argentine soybean meal. However, statistical analysis revealed that only moisture content and water activity showed significant differences between the two origins.

Numerous studies have highlighted the superior nutritional quality of American soybean meal, particularly regarding amino acid digestibility and compositional stability [14,15]. Thermal processing standards, which are well controlled in the United States, allow for protein dispersibility index (PDI) and urease activity levels compatible with good nutritional value and minimal protein denaturation [16]. Moreover, the ratios of digestible lysine to total lysine—indicators of heat treatment quality and preservation of essential amino acids—are generally more favorable for American soybean meals [17]. In comparison, Argentine soybean meal exhibits greater variability, notably in thermal processing and amino acid digestibility [18], which can affect zootechnical performance in practical settings [19]. Differences in industrial methods, storage, and logistics partly explain this variability [20].

5.3. Chemical Composition of Sunflower Meal Mainly Imported from Ukraine to Morocco in 2019–2021

These findings confirm that Ukrainian sunflower meal, as used in Morocco, provides consistent and high-quality nutritional value suitable for the poultry industry. These values are typical of dehulled sunflower meals, whose protein content generally ranges from

33 to 38% [21]. In comparison, soybean meals contain CP levels of 46–48%. Therefore, sunflower meal remains a complementary protein coproduct but not a full substitute for soybean meal.

The moisture levels measured in sunflower meal batches imported from Ukraine between 2019 and 2021 ranged from 9.42% (2019) to 9.93% (2020), with an average of 9.84% in 2021 (Appendix A Tables A17–A19). These values are below the critical threshold of 12%, considered the limit beyond which the risk of mold growth and mycotoxin development increases [22]. Controlled moisture therefore ensures good product stability during storage.

The level of crude fiber (17.561%) is typical of sunflower meal, even when dehulled, and represents a usage limitation, especially in young poultry and broilers due to its negative impact on overall digestibility and feed conversion ratio [23]; conversely, this fiber richness can be beneficial in diets for layers or breeders, promoting digestive health and transit.

Metabolizable energy values ranged from 1553 to 1600 kcal/kg. This low-energy density is well documented [24], limiting its use in diets requiring high caloric density (rapid growth, starter phase). Complementation with dense energy sources (oil, corn) is thus necessary.

5.4. Analysis of Mycotoxin Contamination

5.4.1. Analysis of Mycotoxin Contamination in Argentine Corn Imported

The analysis of Argentine corn samples reveals variable contamination levels due to several mycotoxins. Fumonisin B1 + B2 and deoxynivalenol (DON) recorded the highest mean values, at 1165 ppb and 752 ppb, respectively, with maximum levels reaching 6040 ppb for fumonisins and 3300 ppb for DON. When compared to European Union (EU) regulatory limits for animal feed [25], the average fumonisin level in Argentine corn exceeds the guidance value for poultry feed ingredients, which is set at 20,000 ppb for maize products, but the observed maximum values could pose concerns. For DON, the EU recommends a maximum of 5000 ppb for maize products intended for animal feed, meaning some Argentine corn samples may exceed these limits.

Zearalenone showed an average of 36.99 ppb, remaining below the EU guidance value of 250 ppb for maize feed materials. T-2 toxin levels averaged 13.9 ppb, which is also within the indicative levels set by EFSA [26], although no official EU guidance value exists specifically for T-2 in corn. Ochratoxin A and aflatoxin B1 were detected at very low concentrations; notably, aflatoxin B1 was consistently at 0.2 ppb, well below the strict EU maximum limit of 20 ppb for maize feed materials. (The detailed mycotoxin contamination data of Argentine corn are provided in Appendix A, Table A16).

These findings confirm that while Argentine corn generally complies with European standards for most mycotoxins, particular attention is needed regarding fumonisins and DON due to their high variability and occasional exceedance of EU limits. Systematic monitoring remains essential to guarantee feed safety, especially considering animal health risks associated with chronic exposure [27].

5.4.2. Analysis of Mycotoxin Contamination in Brazilian Corn Imported

The analysis of Brazilian corn samples shows that deoxynivalenol (DON) and fumonisins B1 + B2 are the most prevalent mycotoxins, with mean concentrations of 1354.44 ppb and 1019.52 ppb, respectively. The maximum values reached 3980 ppb for DON and 2120 ppb for fumonisins. When compared to European Union guidance values [25], these levels remain below the recommended maximum limits for maize products intended for animal feed.

Ochratoxin A, T-2 toxin, zearalenone, and aflatoxin B1 were present at much lower levels. Notably, aflatoxin B1 was detected at a constant value of 0.20 ppb, which is well below the EU maximum limit of 20 ppb for feed materials. Zearalenone averaged 21.92 ppb with a maximum of 61.75 ppb, remaining under the EU threshold of 250 ppb.

Despite these being acceptable levels relative to EU standards, the high coefficient of variation for DON (1.04) and zearalenone (0.88) reflects considerable variability between samples. This variability indicates potential contamination risk in certain batches, which is consistent with findings reported by [27], who observed that South American maize, including Brazilian corn, is particularly susceptible to fusarium mycotoxins such as DON and fumonisins due to climate conditions favoring fungal growth. (The detailed mycotoxin contamination data of Brazilian corn are provided in Appendix A, Table A17).

In conclusion, while Brazilian corn appears compliant with European limits overall, continuous monitoring is essential to prevent feed safety issues, especially regarding DON and fumonisin variability. A mycotoxin management strategy adapted to tropical-origin cereals is recommended for feed manufacturers.

5.4.3. Analysis of Mycotoxin Contamination in Ukrainian Corn Imported

Analyses performed on five corn samples imported from Ukraine revealed the presence of several important mycotoxins affecting animal nutrition and feed safety: deoxynivalenol (DON), fumonisins (B1 + B2), ochratoxin A, T-2 toxin, zearalenone, and aflatoxin B1.

Deoxynivalenol (DON): The mean concentration was 456 ppb ($\mu\text{g}/\text{kg}$), ranging from 410 to 560 ppb. According to European regulations (European Commission (EC) Regulation No 1881/2006) [25], DON is known to have immunosuppressive effects and can impair growth performance in animals [28].

Fumonisin B1 + B2: The concentrations were stable at 200 ppb and thus well below safety thresholds, which is reassuring. Fumonisin mainly cause liver and kidney toxicity [29].

Ochratoxin A: It was present at approximately 1.9 ppb ($\mu\text{g}/\text{kg}$), but there are no strict European limits for ochratoxin A, in animal feed,

T-2 Toxin: The mean level was 10.05 ppb, close to the maximum measured value. T-2 toxin is a highly toxic trichothecene with immunosuppressive effects. No specific European regulatory limits exist for T-2 toxin in feed, but levels below 100 ppb are generally considered of low concern [30].

Zearalenone: The mean concentration was 4.9 ppb, with a maximum of 6.86 ppb. The European recommended maximum level for zearalenone in corn is 100 ppb [26], well above the detected values, indicating low contamination. This mycotoxin has estrogenic effects.

Aflatoxin B1: The concentration was very low at 0.2 ppb. The European maximum limit for aflatoxin B1 in animal feed is 20 ppb, confirming minimal contamination. Aflatoxin B1 is known to be the most carcinogenic mycotoxin [31]. (The detailed mycotoxin contamination data of Ukrainian corn are provided in Appendix A, Table A18).

5.5. Interpretation of the Relationship Between Water Activity and Mycotoxin Contamination

Water activity (A_w) plays a critical role in the growth of molds and subsequent production of mycotoxins in stored grains such as maize. In this study, variations in A_w values among the maize samples from different origins were observed, with Brazilian corn showing the highest average A_w (0.716), followed by Argentine corn (0.680), and Ukrainian corn with the lowest A_w (0.662).

These differences in water activity appear to be closely associated with the mycotoxin contamination profile. Indeed, Brazilian corn, which had the highest A_w , also exhibited the highest average levels of deoxynivalenol (DON), ochratoxin A, and relatively high

fumonisin concentrations. In contrast, Ukrainian corn, which showed the lowest Aw, consistently presented the lowest levels of all major mycotoxins, including DON, fumonisins, and zearalenone.

This pattern supports the well-established understanding that higher Aw levels promote fungal growth and mycotoxin biosynthesis, especially under conditions of poor storage, high humidity, or inadequate drying [32,33]. While Aw alone does not entirely determine contamination levels—since environmental conditions, crop management, and post-harvest handling also play important roles [34]—it remains a key predictive factor. Maintaining Aw below critical thresholds (typically < 0.70) is essential for reducing the risk of mold development and mycotoxin accumulation in maize during storage and transport [32–35].

6. Conclusions

This study provides a valuable scientific contribution by delivering a comprehensive chemical and mycotoxin profile of key imported feed ingredients—corn from Argentina, Brazil, and Ukraine; soybean meal from the USA and Argentina; and sunflower meal from Ukraine—used in animal feed production in Morocco. By analyzing and comparing the nutritional quality and contamination risks of these commodities, the research offers critical insights into feed safety, raw material sourcing, and quality control practices. The findings support evidence-based decision making for the Moroccan livestock industry and contribute to the global understanding of feed ingredient variability across different origins.

For corn, moisture content ranged from 12.63% to 14.58%, with water activity (Aw) values between 0.677 and 0.747. While nutritional values such as crude protein, fat, and starch were relatively stable and suitable for poultry feeding, Brazilian corn showed the highest average A_w (0.716), nearing the critical threshold for mold development and correlating with higher mycotoxin levels. In contrast, Ukrainian corn exhibited the lowest A_w (0.662) and consistently lower mycotoxin contamination, highlighting the role of low water activity in ensuring storage safety.

To mitigate mycotoxin-related risks, especially in poultry, the study recommends improving raw material monitoring, using antifungal preservatives or binders, and managing high-moisture batches more carefully.

For soybean meal, the American origin outperformed the Argentine in terms of crude protein, crude fat, metabolizable energy, and digestible lysine. However, statistical differences were only significant for moisture and A_w. These results align with previous studies showing better consistency and processing quality in U.S. SBM.

Sunflower meal from Ukraine showed a stable and improving nutritional profile over three years, with increased crude protein (35.97–36.99%) and metabolizable energy, and decreased fiber. Despite lower protein and amino acid content compared to SBM, SFM remains a valuable complementary protein source, particularly for layers and breeders due to its high fiber content. ME values for SFM were lower (1553–1600 kcal/kg), as expected, but consistent across years.

Regular analysis of the chemical composition of these raw materials is therefore essential to ensure feed safety, allow precise diet formulation, and optimize zootechnical performance. Moreover, new alternative sources are beginning to be explored to diversify nutrient inputs. In this regard, a recent study [36] reports that non-industrial Moroccan hemp seed ecotypes can be included at low levels in laying hen diets without adverse effects on performance, partially replacing corn, soybean, or other oilseeds, thus opening new perspectives in feed formulation.

These findings provide valuable insights for poultry and livestock feed formulators, offering a general overview of the nutritional quality and potential risks associated with

different ingredient origins. Special attention should be paid to water activity, which strongly influences the development of mycotoxins. In particular, Argentine corn may pose a risk for fumonisin and T-2 toxin contamination, while Brazilian corn may require close monitoring for DON and ochratoxin A. It is therefore essential to systematically test each incoming batch to ensure feed safety and performance.

This study successfully highlighted the nutritional advantages and limitations associated with each origin for the three raw materials, providing a scientific basis for making optimal sourcing decisions. It also lays the groundwork for future field-based research aimed at evaluating the impact of ingredient origin on animal performance. Such studies would enable a critical analysis of additional variables linking nutrients to animals, including digestibility, nutrient absorption, and overall zootechnical outcomes.

Author Contributions: N.E.B. designed the experimental protocol, performed the statistical analysis, interpreted the results, and drafted the first version of the manuscript. H.H. validated the experimental protocol and contributed to writing the discussion section. B.B. performed statistical analysis and approved the final version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original data from the paper are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declares that there are no conflicts of interest regarding the publication of this article.

Abbreviations

The following abbreviations are used in this manuscript:

EMp	Metabolizable Energy Poultry
Aw	Water Activity
CP	Crude Protein
CF	Crude Fat
CFb	Crude Fiber
MM	Mineral Matter/Ash
ME	Metabolizable Energy
SBM	Soybean Meal
SFM	Sunflower Meal
DON	Deoxynivalenol
T-2	T-2 toxin
PDI	Protein Dispersibility Index

Appendix A

Table A1. Nutritional Composition of Argentine Corn Imported in 2019.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	98	12.792	8.660	14.330	1.212
Water Activity (Aw)	51	0.679	0.530	0.965	0.081
Crude Protein (%)	91	7.317	6.470	9.160	0.337
Crude Fat (%)	46	4.150	3.800	4.600	0.196
Crude Fiber (%)	39	2.059	1.800	2.400	0.112
Ash (%)	97	1.212	0.990	2.150	0.164
Starch (%)	36	63.800	62.000	65.800	1.052
Metabolizable Energy (kcal/kg)	39	3343.077	3291.000	3483.000	50.083
Digestible Lysine (%)	40	0.224	0.209	0.255	0.008
Digestible Methionine + Cysteine (%)	40	0.304	0.282	0.328	0.009
Digestible Threonine (%)	40	0.240	0.224	0.286	0.010

Table A2. Nutritional Composition of Argentine Corn Imported in 2020.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	16	13.439	12.090	14.160	0.661
Water Activity (Aw)	10	0.694	0.588	0.728	0.041
Crude Protein (%)	16	7.363	7.000	8.400	0.385
Crude Fat (%)	7	3.929	3.900	4.000	0.049
Crude Fiber (%)	6	1.850	1.800	1.900	0.055
Ash (%)	16	1.126	1.000	1.300	0.087
Starch (%)	6	64.083	62.100	66.000	1.569
Metabolizable Energy (kcal/kg)	6	3318.000	3296.000	3349.000	23.126
Digestible Lysine (%)	6	0.219	0.204	0.242	0.016
Digestible Methionine + Cysteine (%)	6	0.307	0.302	0.319	0.007
Digestible Threonine (%)	6	0.243	0.232	0.266	0.013

Table A3. Nutritional Composition of Argentine Corn Imported in 2021.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	49	13.022	10.890	13.950	0.606
Water Activity (Aw)	29	0.677	0.640	0.711	0.025
Crude Protein (%)	49	7.306	6.370	7.910	0.378
Crude Fat (%)	17	4.071	3.700	4.500	0.202
Crude Fiber (%)	15	2.000	1.800	2.300	0.136
Ash (%)	49	1.145	0.710	1.340	0.107
Starch (%)	15	64.207	62.600	67.200	1.129

Table A3. *Cont.*

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Metabolizable Energy (kcal/kg)	9	3332.111	3299.000	3390.000	26.141
Digestible Lysine (%)	9	0.218	0.205	0.230	0.009
Digestible Methionine + Cysteine (%)	9	0.299	0.267	0.311	0.013
Digestible Threonine (%)	9	0.231	0.223	0.240	0.006

Table A4. Nutritional Composition of Brazilian Corn Imported in 2019.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	45	12.625	9.900	13.830	1.071
Water Activity (Aw)	24	0.716	0.660	0.761	0.032
Crude Protein (%)	48	7.483	6.470	9.400	0.614
Crude Fat (%)	21	4.110	3.700	4.600	0.239
Crude Fiber (%)	19	1.912	1.030	2.300	0.372
Ash (%)	42	1.174	0.970	1.400	0.104
Starch (%)	15	63.800	61.300	66.100	1.167
Metabolizable Energy (kcal/kg)	15	3352.200	3308.000	3419.000	33.158
Digestible Lysine (%)	18	0.219	0.160	0.264	0.029
Digestible Methionine + Cysteine (%)	12	0.313	0.299	0.348	0.013
Digestible Threonine (%)	15	0.253	0.237	0.294	0.018

Table A5. Nutritional Composition of Brazilian Corn Imported in 2021.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	3	14.583	14.530	14.660	0.068
Water Activity (Aw)	3	0.721	0.716	0.731	0.008
Crude Protein (%)	3	7.013	6.950	7.060	0.057
Ash (%)	3	1.267	1.260	1.280	0.012

Table A6. Nutritional Composition of Ukrainian Corn Imported in 2019.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	6	13.020	11.630	13.440	0.721
Water Activity (Aw)	3	0.681	0.679	0.684	0.003
Crude Protein (%)	6	7.237	7.030	7.400	0.124
Crude Fat (%)	3	4.167	4.100	4.200	0.058
Crude Fiber (%)	3	2.133	2.100	2.200	0.058
Ash (%)	6	1.160	1.110	1.200	0.045
Starch (%)	3	64.067	63.100	64.800	0.874
Metabolizable Energy (kcal/kg)	3	3343.667	3311.000	3365.000	28.729
Digestible Lysine (%)	3	0.222	0.219	0.224	0.003

Table A6. Cont.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Digestible Methionine + Cysteine (%)	3	0.301	0.293	0.306	0.007
Digestible Threonine (%)	3	0.235	0.233	0.237	0.002

Table A7. Nutritional Composition of Ukrainian Corn Imported in 2020.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	3	13.403	13.390	13.420	0.015
Water Activity (Aw)	3	0.747	0.746	0.748	0.001
Crude Protein (%)	3	7.107	7.100	7.110	0.006
Ash (%)	3	1.090	1.090	1.090	0.000

Table A8. Nutritional Composition of Soybean Meal Imported from the USA in 2019.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	62	11.106	8.700	12.890	0.961
Water Activity (Aw)	29	0.663	0.544	0.728	0.036
Crude Protein (%)	59	47.246	45.010	49.560	1.014
Crude Fat (%)	27	2.296	1.200	3.200	0.623
Crude Fiber (%)	27	3.689	3.100	4.300	0.352
Ash (%)	62	6.327	5.420	6.800	0.290
Starch (%)	24	0.546	0.300	1.000	0.144
Metabolizable Energy (kcal/kg)	21	2390.667	2335.000	2440.000	29.827
Digestible Lysine (%)	21	2.580	2.473	2.656	0.044
Digestible Methionine + Cysteine (%)	21	1.113	1.087	1.147	0.018
Digestible Threonine (%)	21	1.523	1.472	1.588	0.031
Protein Dispersibility Index (PDI. %)	29	11.008	7.850	13.100	1.326
Urease Activity (mg N/g/min)	3	0.045	0.029	0.059	0.015
Protein Solubility in KOH (%)	21	78.738	75.600	82.000	1.615

Table A9. Nutritional Composition of Soybean Meal Imported from the USA in 2020.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	3	11.020	11.010	11.030	0.010
Water Activity (Aw)	3	0.648	0.648	0.649	0.001
Crude Protein (%)	3	46.830	46.760	46.900	0.070
Ash (%)	3	5.963	5.960	5.970	0.006

Table A10. Nutritional Composition of Soybean Meal Imported from the USA in 2021.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	38	11.530	10.300	12.700	0.501

Table A10. Cont.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Water Activity (Aw)	21	0.664	0.618	0.704	0.029
Crude Protein (%)	38	46.660	44.950	47.750	0.766
Crude Fat (%)	17	2.406	2.000	4.300	0.503
Crude Fiber (%)	15	3.633	3.300	3.900	0.150
Ash (%)	38	6.427	5.090	6.800	0.317
Starch (%)	15	0.880	0.600	1.600	0.248
Metabolizable Energy (kcal/kg)	15	2348.800	2323.000	2380.000	14.284
Digestible Lysine (%)	15	2.543	2.503	2.579	0.021
Digestible Methionine + Cysteine (%)	15	1.084	1.053	1.117	0.015
Digestible Threonine (%)	15	1.505	1.483	1.537	0.014
Protein Dispersibility Index (PDI. %)	23	12.763	7.900	17.700	2.445
Urease Activity (mg N/g/min)	0		0.000	0.000	
Protein Solubility in KOH (%)	23	75.089	70.190	80.600	3.096
Reactive Lysine / Total Lysine (%)	15	2.608	2.552	2.750	0.049
PCI (Protein Quality Index)	15	89.368	88.181	90.085	0.436

Table A11. Nutritional Composition of Argentine Soybean Meal Imported in 2019.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	14	10.561	8.820	12.300	0.998
Water Activity (Aw)	6	0.630	0.593	0.673	0.026
Crude Protein (%)	15	46.764	43.600	49.850	1.278
Crude Fat (%)	8	2.075	1.600	3.400	0.639
Crude Fiber (%)	6	3.667	3.400	3.800	0.137
Ash (%)	14	6.414	6.030	6.700	0.202
Starch (%)	6	0.717	0.600	0.800	0.075
Metabolizable Energy (kcal/kg)	6	2365.833	2309.000	2472.000	66.704
Digestible Lysine (%)	6	2.554	2.534	2.576	0.017
Digestible Methionine + Cysteine (%)	6	1.111	1.100	1.118	0.007
Digestible Threonine (%)	6	1.525	1.510	1.542	0.015
Protein Dispersibility Index (PDI. %)	9	11.581	9.800	15.700	1.832
Urease Activity (mg N/g/min)	2	0.042	0.032	0.052	0.014
Protein Solubility in KOH (%)	8	77.850	76.000	79.300	1.189

Table A12. Nutritional Composition of Argentine Soybean Meal Imported in 2021.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	5	11.128	10.860	11.360	0.248
Water Activity (Aw)	4	0.664	0.630	0.677	0.022

Table A12. *Cont.*

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Crude Protein (%)	5	46.456	45.580	47.360	0.771
Ash (%)	5	6.676	6.210	6.970	0.290
Protein Dispersibility Index (PDI. %)	1	12.230	12.230	12.230	
Protein Solubility in KOH (%)	1	82.900	82.900	82.900	

Table A13. Nutritional Composition of Ukrainian Sunflower Meal Imported in 2019.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	68	9.417	7.670	11.900	0.941
Water Activity (Aw)	33	0.654	0.480	0.732	0.065
Crude Protein (%)	73	35.971	29.790	39.150	1.567
Crude Fat (%)	34	1.862	1.400	2.500	0.257
Crude Fiber (%)	32	17.966	14.500	20.400	1.244
Ash (%)	68	6.435	5.400	7.470	0.512
Metabolizable Energy (kcal/kg)	28	1553.607	1389.000	1628.000	44.899
Digestible Lysine (%)	28	1.132	0.908	1.196	0.057
Digestible Methionine + Cysteine (%)	28	1.168	0.922	1.237	0.062
Digestible Threonine (%)	28	1.057	0.826	1.121	0.059

Table A14. Nutritional Composition of Ukrainian Sunflower Meal Imported in 2020.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	15	9.779	6.620	11.310	1.133
Water Activity (Aw)	9	0.682	0.645	0.732	0.038
Crude Protein (%)	15	36.221	33.450	38.070	1.157
Crude Fat (%)	6	2.150	1.900	2.500	0.259
Crude Fiber (%)	6	17.683	16.000	20.200	1.687
Ash (%)	15	6.069	5.670	6.700	0.311
Starch (%)	0		0.000	0.000	
Metabolizable Energy (kcal/kg)	6	1583.833	1520.000	1616.000	35.930
Digestible Lysine (%)	6	1.190	1.089	1.245	0.057
Digestible Methionine + Cysteine (%)	6	1.209	1.112	1.266	0.055
Digestible Threonine (%)	6	1.083	0.983	1.148	0.061

Table A15. Nutritional Composition of Ukrainian Sunflower Meal Imported in 2021.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Moisture (%)	34	9.836	8.960	11.060	0.495

Table A15. Cont.

Parameter	Number of Samples (n)	Mean	Min	Max	Standard Deviation
Water Activity (Aw)	17	0.662	0.620	0.725	0.034
Crude Protein (%)	34	36.992	35.010	40.430	1.211
Crude Fat (%)	11	1.845	1.600	2.000	0.144
Crude Fiber (%)	6	17.033	16.500	18.000	0.554
Ash (%)	33	6.794	5.590	7.420	0.521
Metabolizable Energy (kcal/kg)	6	1600.167	1574.000	1622.000	22.067
Digestible Lysine (%)	6	1.133	1.107	1.152	0.015
Digestible Methionine + Cysteine (%)	6	1.229	1.184	1.274	0.036
Digestible Threonine (%)	6	1.073	1.052	1.097	0.016

Table A16. Analysis of mycotoxin contamination in imported Argentine corn.

Argentine Corn	Deoxynivalenol (DON) (ppb)	Fumonisin B1 + B2 (ppb)	Ochratoxin (ppb)	T-2 Toxin (ppb)	Zearalenone (ppb)	Aflatoxin B1 (ppb)
Number of samples	48.00	39.00	48.00	42.00	48.00	48.00
Mean	752.81	1165.26	2.26	13.91	36.99	0.20
Minimum	270.00	210.00	1.00	10.00	0.00	0.20
Maximum	3300.00	6040.00	6.22	71.34	199.25	0.20
Standard deviation	622.13	1241.52	1.06	12.09	43.31	0.00
Coefficient of variation	0.83	1.07	0.47	0.87	1.17	0.00

Table A17. Analysis of mycotoxin contamination in imported Brazilian corn.

Brazilian Corn	Deoxynivalenol (DON) (ppb)	Fumonisin B1 + B2 (ppb)	Ochratoxin (ppb)	T-2 Toxin (ppb)	Zearalenone (ppb)	Aflatoxin B1 (ppb)
Number of samples	18.00	21.00	21.00	21.00	21.00	21.00
Mean	1354.44	1019.52	3.02	10.00	21.92	0.20
Minimum	200.00	280.00	1.90	10.00	2.62	0.20
Maximum	3980.00	2120.00	7.15	10.00	61.75	0.20
Standard deviation	1414.25	628.77	1.70	0.00	19.36	0.00
Coefficient of variation	1.04	0.62	0.56	0.00	0.88	0.00

Table A18. Analysis of mycotoxin contamination in imported Ukrainian corn.

Ukrainian Corn	Deoxynivalenol (DON) (ppb)	Fumonisin B1 + B2 (ppb)	Ochratoxin (ppb)	T-2 Toxin (ppb)	Zearalenone (ppb)	Aflatoxin B1 (ppb)
Number of samples	5.00	2.00	5.00	5.00	5.00	5.00
Mean	456.00	200.00	1.90	10.05	4.90	0.20
Minimum	410.00	200.00	1.90	10.00	3.10	0.20
Maximum	560.00	200.00	1.90	10.26	6.86	0.20
Standard deviation	62.69	0.00	0.00	0.12	1.57	0.00
Coefficient of variation	0.14	0.00	0.00	0.01	0.32	0.00

Table A19. Mycotoxin profiling of maize batches analyzed in this Study.

		Mean	Minimum	Maximum
Deoxynivalenol DON (ppb)	Argentine Corn 1	752.813	270.000	3300.000
	Brazilian corn 2	1354.444	200.000	3980.000
	Ukrainian corn 3	456.000	410.000	560.000
	Total	884.437	200.000	3980.000
Fumonisin B1 + B2 (ppb)	Argentine Corn 1	1165.256	210.000	6040.000
	Brazilian corn 2	1019.524	280.000	2120.000
	Ukrainian corn 3	200.000	200.000	200.000
	Total	1084.758	200.000	6040.000
Ochratoxin (ppb)	Argentine Corn 1	2.259	1.000	6.220
	Brazilian corn 2	3.019	1.900	7.150
	Ukrainian corn 3	1.900	1.900	1.900
	Total	2.451	1.000	7.150
Toxin T-2 (ppb)	Argentine Corn 1	13.905	10.000	71.340
	Brazilian corn 2	10.000	10.000	10.000
	Ukrainian corn 3	10.052	10.000	10.260
	Total	12.416	10.000	71.340
Zearalenone (ppb)	Argentine Corn 1	36.988	0.000	199.250
	Brazilian corn 2	21.920	2.620	61.750
	Ukrainian corn 3	4.904	3.100	6.860
	Total	30.544	0.000	199.250
Aflatoxin B1(ppb)	Argentine Corn 1	0.200	0.200	0.200
	Brazilian corn 2	0.200	0.200	0.200
	Ukrainian corn 3	0.200	0.200	0.200
	Total	0.200	0.200	0.200

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