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# Pet food safety at risk? Investigating toxic metal contamination in Lebanon and the UAE

Fatima Haydous,†[a] Hussein F. Hassan,†[b] Aya Shehab,[a] Nisreen Alwan,[c] Mireille Serhan,[d] Hani Dimassi[e] and Elias Akoury*[a]

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Our study investigates the presence of toxic metals in pet food stock keeping units (SKUs) marketed in Lebanon ($n$ = 75) and the United Arab Emirates (UAE) ($n$ = 121) using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). The study quantified nine metals: chromium (Cr), cobalt (Co), copper (Cu), zinc (Zn), arsenic (As), molybdenum (Mo), cadmium (Cd), mercury (Hg), and lead (Pb). Dry pet food exhibited higher concentrations compared to wet pet food, particularly for Cu (30.302 mg kg$^{-1}$ *vs.* 4.861 mg kg$^{-1}$, $p < 0.001$), Zn (350.223 mg kg$^{-1}$ *vs.* 35.965 mg kg$^{-1}$, $p < 0.001$), and Pb (0.981 mg kg$^{-1}$ *vs.* 0.421 mg kg$^{-1}$, $p < 0.039$). This suggests that moisture content affects metal retention. Notably, Cd concentrations were higher in wet food (0.296 mg kg$^{-1}$ *vs.* 0.102 mg kg$^{-1}$, $p < 0.045$), indicating differential metal solubility and retention mechanisms. Cat food samples contained higher Cd levels than dog food (0.251 mg kg$^{-1}$ *vs.* 0.112 mg kg$^{-1}$), whereas Zn and Cu concentrations were significantly higher in dog food. Pb and As exceeded safety thresholds, raising concerns about contamination sources and health risks for pets. These findings highlight the need for stringent monitoring of toxic metals in pet food and further research into contamination sources and their potential health impacts for pets.

## Introduction

The demand for commercial pet food has grown extensively worldwide, with most pet owners preferring processed food due to its convenience and cost-effectiveness. However, pet food safety remains a concern, as contamination with chemical, physical, and microbiological hazards, including cyanuric acid, metals, *Salmonella*, *Listeria*, and molds, can pose risks to both pets and their owners.[1–4] Contaminated pet food has been linked to human illnesses through direct and indirect exposure, and regulatory agencies like the U.S. Food and Drug Administration (FDA) and European Union (EU) authorities have set safety standards.[5,6] However, gaps in policies in several regions remain high where no in-depth studies on pet food microbiological safety and toxic metal contamination have been conducted. Two recent studies assessed microbiological hazards in pet food marketed in Lebanon and the UAE, providing baseline data and raising awareness of potential contamination risks.[7,8] Equally important, the potential presence of toxic metals in pet food raises growing concerns due to the significant long-term health risks they pose to animals. Toxic metals such as lead (Pb), arsenic (As), cadmium (Cd), and mercury (Hg) are non-biodegradable, persistent in the environment, and are known to accumulate in biological systems.[9–11] These elements can enter pet food through contaminated raw materials, industrial pollution, and manufacturing processes. As domesticated animals, particularly cats and dogs, consume commercial pet food daily, prolonged exposure to these contaminants may lead to severe health issues, including neurological disorders, organ damage, and immune suppression. The sources of toxic metal contamination in pet food are diverse. Environmental pollution, agricultural practices, and industrial activities contribute to the accumulation of toxic metals in ingredients such as meat, fish, grains, and vegetables.[12,13] Industrial pollution and pesticide residues further contribute to contamination in plant-based ingredients.[14] Additionally, poor-quality raw materials and inadequate regulatory oversight can further exacerbate contamination risks. While regulatory agencies such as the FDA and the Association of American Feed Control Officials (AAFCO) have established safety guidelines, studies have shown that certain pet food products exceed the permissible limits for toxic metals, raising concerns about their long-term effects on animal health.[15–17]

Toxic metals have no biological function and are toxic even at low concentrations. Chronic exposure in pets has been linked to

[a]Department of Physical Sciences, School of Arts and Sciences, Lebanese American University, Beirut 1102-2801, Lebanon. E-mail: elias.akoury@lau.edu.lb; Tel: +961 1 786456
[b]Department of Nutrition and Food Sciences, School of Arts and Sciences, Lebanese American University, Beirut 1102-2801, Lebanon
[c]Environmental and Public Health Department, College of Health Sciences, Abu Dhabi University, P.O. Box 59911, Abu Dhabi, United Arab Emirates
[d]Department of Nutritional Sciences, Faculty of Health Sciences, University of Balamand, Koura, Lebanon
[e]School of Pharmacy, Lebanese American University, Byblos, Lebanon
† These authors contributed equally.

various health problems. For instance, arsenic-containing compounds are highly toxic, affecting kidney and liver function, and have been associated with cancer in animals.[18] Cd accumulates in the kidneys and liver, leading to nephrotoxicity, bone demineralization, and immune suppression.[19] Exposure to Pb in pets can cause neurological dysfunction, anemia, gastrointestinal distress, and reproductive issues.[20] Methylmercury, commonly found in fish-based pet foods, is neurotoxic and can result in tremors, behavioral changes, and cognitive impairment.[21] While Cr(III) is an essential trace element, Cr(VI) is a known carcinogen linked to respiratory and gastrointestinal toxicity.[22] Comparative research analyzing toxic metal concentrations in commercial pet food relative to the FDA maximum tolerable levels (MTL) has revealed concerning findings where certain toxic metals exceeded established safety thresholds.[23] Importantly, the co-exposure to microbial pathogens and toxic metals in pet food can lead to synergistic health effects, including impaired immunity, increased toxin absorption, and disrupted gut microbiota, which collectively heighten susceptibility to infections and disease. This interaction may also intensify oxidative stress and inflammation, potentially causing damage to vital organs such as the liver, kidneys, and nervous system.[7,8]

Several recent studies have investigated the presence of toxic metals in commercial pet foods across different countries, revealing concerning trends in contamination and regulatory gaps. In this context, it is important to note that the criteria used to distinguish between "developed" and "developing" countries is based on the classification provided by the United Nations Industrial Development Organization (UNIDO) in its 2024 report,[24] as well as supplementary references from the World Bank.[25] Developed countries, also known as high-income or industrialized nations, are typically characterized by high per capita income, diversified and technologically advanced economies, strong infrastructure, high Human Development Index (HDI) values, and well-established healthcare, education, and regulatory systems. In contrast, developing countries often referred to as emerging or low- and middle-income nations with low per capita income, less diversified economies often reliant on agriculture or basic manufacturing, lower HDI scores, and limited access to quality infrastructure, healthcare, and education. These countries are usually undergoing efforts to enhance industrialization, economic stability, governance and regulatory systems.

In a study conducted in an urban region of Poland, toxic metal levels were assessed in the blood serum of 48 healthy pet dogs.[26] The results indicated that smaller-sized dogs exhibited higher concentrations of toxic metals compared to larger breeds. Furthermore, dogs fed commercial pet food had significantly greater toxic metal burdens than those consuming homemade diets. A study in the UAE analyzed 12 brands of cat food and found that Pb concentrations in wet foods exceeded the EU maximum level while dry foods had lower Pb levels.[27] Cd was detected with a few samples exceeding the EU threshold of 0.1 mg $kg^{-1}$; while As and Hg were generally below international limits; and essential elements like Cu and Zn were within AAFCO-recommended ranges. In Brazil, a similar study covered a larger survey of 95 pet food products, including dog and cat foods, and reported Pb levels with approximately 23% of samples exceeding safe limits.[23] Cd levels ranged from 0.02 to 0.15 mg $kg^{-1}$, and Hg was notably higher in fish-based products up to 0.09 mg $kg^{-1}$. The Brazilian study also included essential elements such as Fe, Zn, Cu, Mn, and Se, revealing significant variability and frequent mismatches between measured and labeled values. Another study conducted in South Africa focused on 20 brands and detected Pb concentrations with nearly 30% of samples exceeding the EU's maximum level.[28] Cd ranged from 0.04 to 0.22 mg $kg^{-1}$, while Cr and Ni were detected. A recent study analyzed 93 imported cat and dog food products sold in China for toxic metals using flame atomic absorption and atomic fluorescence spectrometry.[29] Cr and As were found in all samples, with particularly high levels in dry food, while some products exceeded national safety limits for Pb and Cr. Risk assessment revealed that dietary exposure, especially to Cr, poses a potential health hazard to pets, highlighting widespread contamination and long-term risk. Although none of the studies indicated immediate toxicity, all raised concerns over chronic exposure risks, particularly for animals consuming the same brand over extended periods. Common across the three studies were the lack of country-specific regulations for pet food safety and insufficient oversight, particularly in developing economies. These findings underscore the need for harmonized international standards, transparent labeling, regular quality control, and further research into the long-term health effects of trace metal exposure in companion animals.

Chronic exposure to toxic metals poses severe health risks to pets, particularly canines. Lead has been associated with anemia, blindness, epileptic seizures, and bone sclerosis. As exposure has been linked to ulcerative dermatitis, while Cd has been shown to disrupt male reproductive function and impair pancreatic activity.[30] Given these significant health concerns, stringent regulation of toxic metal concentrations in pet food is imperative. Strengthening quality control measures and enforcing rigorous regulatory oversight are essential to ensuring the long-term safety of pet food products and safeguarding animal health.[31,32] Toxic metal contamination was reported in widely consumed food products and herbs in Lebanon, such as parsley,[33] thyme,[34] rice,[35] breast milk,[36] and infant formula.[37] These findings underscore the need stronger food safety regulations, enhanced quality control measures, and increased consumer awareness to mitigate health risks associated with dietary exposure to toxic metals. Given the increasing awareness of food safety and pet welfare, it is crucial to investigate the presence of toxic metals in pet food, understand their potential health implications, and advocate for stricter quality control measures. The aim of our study is to determine the levels of toxic metals in pet food marketed in Lebanon and UAE, and to estimate pet exposure in these populations.

## Materials and methods

### Sample collection

Market screening was conducted in Lebanon and the UAE in Fall 2021. All pet shops were visited to identify available stock keeping units (SKUs) of dry and wet pet food. Identified SKUs (75 in Lebanon and 121 in the UAE) were then collected for

 

Table 1 Characteristics of commercial wet and dry pet food ($n = 196$)

| | Lebanon | | UAE | | Total | |
|---|---|---|---|---|---|---|
| | *N* | % | *N* | % | *N* | % |
| **Total** | 75 | 38.30% | 121 | 61.70% | 196 | 100% |
| **Type of food** | | | | | | |
| Dry | 53 | 70.70% | 28 | 23.10% | 81 | 41.30% |
| Wet | 22 | 29.30% | 93 | 76.90% | 115 | 58.70% |
| **Pet** | | | | | | |
| Cats | 50 | 66.70% | 97 | 80.20% | 147 | 75.00% |
| Dogs | 25 | 33.30% | 24 | 19.80% | 49 | 25.00% |
| **Country** | | | | | | |
| Australia | 1 | 1.30% | 7 | 5.80% | 8 | 4.10% |
| Brazil | 7 | 9.30% | 0 | 0.00% | 7 | 3.60% |
| Czech | 10 | 13.30% | 0 | 0.00% | 10 | 5.10% |
| France | 8 | 10.70% | 15 | 12.40% | 23 | 11.70% |
| Germany | 1 | 1.30% | 10 | 8.30% | 11 | 5.60% |
| Hungary | 0 | 0.00% | 13 | 10.70% | 13 | 6.60% |
| Italy | 13 | 17.30% | 2 | 1.70% | 15 | 7.70% |
| Lebanon | 5 | 6.70% | 0 | 0.00% | 5 | 2.60% |
| Malta | 1 | 1.30% | 0 | 0.00% | 1 | 0.50% |
| New Zealand | 5 | 6.70% | 0 | 0.00% | 5 | 2.60% |
| Portugal | 4 | 5.30% | 0 | 0.00% | 4 | 2.00% |
| Spain | 5 | 6.70% | 0 | 0.00% | 5 | 2.60% |
| Thailand | 0 | 0.00% | 45 | 37.20% | 45 | 23.00% |
| Turkey | 6 | 8.00% | 0 | 0.00% | 6 | 3.10% |
| UAE | 5 | 6.70% | 0 | 0.00% | 5 | 2.60% |
| UK | 2 | 2.70% | 7 | 5.80% | 9 | 4.60% |
| USA | 2 | 2.70% | 22 | 18.20% | 24 | 12.20% |
| **Country of origin** | | | | | | |
| Developed | 52 | 69.30% | 76 | 62.80% | 128 | 65.30% |
| Developing | 23 | 30.70% | 45 | 37.20% | 68 | 34.70% |

analysis. Sample details, including pet food type, pet type (cat/dog), and country of origin, are provided in Table 1. All samples were stored in their original packaging and opened only before analysis. Pet food samples (0.5 g) were digested using a Multiwave ECO microwave digestion system (Anton Paar GmbH, Graz, Austria) equipped with a rotor for 16 vessels (Rotor 24HVT50, Anton Paar GmbH, Graz, Austria) after adding 8 mL of 69% nitric acid and 2 mL of 30% hydrogen peroxide to each of the samples. The sample digestion procedure was performed as follows: (1) 850 W at 180 °C for 10 min and (2) 850 W at 22 °C for 1 min for cooling. After microwave digestion, 2 mL HCl were added to sample solutions, and the digested samples were then transferred into 50 mL flasks. The contents were diluted 5 times with 3% nitric acid prepared with ultrapure deionized water and stored at 4 °C until analysis by ICP-MS. Two stock solutions were prepared from each metal to prepare standards for the calibration curve in ICP-MS.

### Sample analysis

Inductively Coupled Plasma-Mass Spectrometry (ICP-MS iCAP Q/iCAP RQ ICP-MS, ThermoFisher Scientific Inc., Bremen, Germany) operating with argon gas of spectral purity (99.9995%) was used for the determination and quantification of toxic metals in pet food samples. Operating conditions and acquisition parameters are illustrated In Table 2. Before each experiment, ICP-MS was tuned using iCAP Q/RQ TUNE aqueous multi-element standard solution in 2% $HNO_3$ + 0.5% HCl solution (Thermo scientific, Bremen, Germany). The torch position, ion lenses, gas output, resolution axis (10% of peak height), and background (<20 shots) were optimized with the tuning solution (1 mg $L^{-1}$) The correlation coefficients for all the calibration curves were at least 0.9999, reflecting a strong linear relationship throughout the ranges of concentrations under study. All measurements were conducted using the full quantitative mode analysis while measuring several isotopes of the elements and checking the isotopic ratio in the digested samples to confirm the absence of polyatomic interferences. The limit of detection (LOD) for each element was calculated by blank determination as 3 times standard deviation of 20 blank replicates. Similarly, the limit of quantification (LOQ) was calculated as 2 times LOD for each element.

### Statistical analysis

Concentration values for all toxic metals were incorporated into SPSS V27. The distributions of metal concentrations were tested for normality, and when deviations were detected, analyses accounted for non-normality using nonparametric analysis tests. Differences in mean metal concentrations according to type (wet *vs.* dry), pet type (dog *vs.* cat), and country of origin (developed *vs.* developing) were tested using the independent *t* test when conditions of normality were met, otherwise the Mann–Whitney *U* test was used. All analyses were carried at the 0.05 significance level.

## Results and discussion

A total of 196 pet food samples were analyzed, with 38.3% (75 samples) sourced from Lebanon and 61.7% (121 samples) from the UAE (Table 1). This distribution suggests a greater variety or

Table 2 ICP-MS operating conditions and acquisition parameters

| Nebulizer | Spray chamber | Cell geometry | Sampling cone | Skimmer cone | RF power | Plasma gas flow |
|---|---|---|---|---|---|---|
| 0.5 mL $min^{-1}$ | 2.70 °C | Octopole | Nickel 1.1 mm | Nickel 0.75 mm | 400–1600 W | 12 L $min^{-1}$ |
| **Nebulizer flow** | **Expansion** | **Intermediate** | **Analyzer** | **Helium gas flow** | **Frequency** | **Replicates** |
| 1.07 mL $min^{-1}$ | 2.02 mbar | $10^{-4}$ mbar | $10^{-6}$ mbar | 3.5 mL $min^{-1}$ | 2 MHz | 3 |

Table 3 Detected concentrations of toxic metals (mg kg$^{-1}$) in dry food (LOD: limit of detection, LOQ: limit of quantification). Samples 1 to 28 are originating from UAE while samples from 29 to 81 are originating from Lebanon

| Sample | $^{52}$Cr | $^{59}$Co | $^{63}$Cu | $^{64}$Zn | $^{75}$As | $^{98}$Mo | $^{114}$Cd | $^{200}$Hg | $^{208}$Pb |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.5376 | 0.2884 | 34.8933 | 298.8862 | 0.3101 | 1.2110 | 0.1515 | 0.9332 | 1.1300 |
| 2 | 2.7231 | 0.5958 | 36.8691 | 421.5777 | 0.6833 | 1.1122 | 0.1297 | 1.2245 | 4.0445 |
| 3 | 2.6457 | 0.2012 | 38.8450 | 396.8694 | 0.5691 | 0.9942 | 0.1299 | 1.1840 | 3.8969 |
| 4 | 2.6654 | 0.3911 | 31.5347 | 372.1611 | 0.1596 | 1.3695 | 0.1296 | 1.1163 | 4.4483 |
| 5 | 2.1817 | 0.2984 | 33.4326 | 437.5619 | 0.1644 | 1.7203 | 0.1302 | 1.1541 | 4.9998 |
| 6 | 2.2748 | 0.2804 | 27.9838 | 372.2806 | 0.1955 | 1.5712 | 0.1289 | 1.2959 | 0.6736 |
| 7 | 3.0648 | 0.2512 | 27.6607 | 342.8105 | 0.1721 | 1.5269 | 0.1315 | 1.1587 | 0.7088 |
| 8 | 2.9622 | 0.5563 | 33.5938 | 368.4736 | 0.1838 | 1.6114 | 0.0921 | 1.2562 | 1.0158 |
| 9 | 2.8596 | 0.5630 | 32.2373 | 403.1396 | 0.1993 | 1.3363 | 0.1118 | 1.2712 | 1.5842 |
| 10 | 2.2056 | 0.2465 | 23.6173 | 310.7873 | 0.1049 | 1.0361 | 0.1019 | 1.3195 | 2.6751 |
| 11 | 4.3433 | 0.3819 | 35.7523 | 374.7578 | 0.1610 | 1.3924 | 0.0560 | 1.2311 | 0.9422 |
| 12 | 3.7533 | 0.3982 | 35.3329 | 438.7284 | 0.2171 | 2.4647 | 0.0860 | 1.0816 | 1.3161 |
| 13 | 3.4008 | 0.3829 | 35.0685 | 389.0123 | 0.2643 | 3.5684 | 0.0048 | 0.9320 | 0.9007 |
| 14 | 4.0816 | 2.3385 | 34.8041 | 431.6932 | 0.1951 | 1.1418 | 0.1119 | 1.0797 | 0.9074 |
| 15 | 4.1333 | 2.9634 | 35.4155 | 449.0937 | 0.5194 | 1.4123 | 0.0769 | 0.8153 | 1.1117 |
| 16 | 3.4530 | 3.5882 | 26.6918 | 302.7557 | 0.1382 | 1.0246 | 0.1542 | 1.3107 | 0.8054 |
| 17 | 3.1676 | 2.1157 | 28.5292 | 301.0838 | 0.1368 | 1.2825 | 0.1546 | 1.2505 | 1.9523 |
| 18 | 3.3691 | 2.8520 | 29.2275 | 438.9151 | 0.4228 | 1.1499 | 0.1363 | 1.1566 | 1.3763 |
| 19 | 3.5707 | 2.4838 | 23.8867 | 405.3853 | 0.4488 | 1.6517 | 0.1284 | 1.2812 | 1.5023 |
| 20 | 3.0894 | 0.3832 | 18.5460 | 217.1449 | 0.2163 | 1.2086 | 0.0921 | 1.3611 | 1.0261 |
| 21 | 4.5831 | 1.1095 | 42.0351 | 274.2391 | 0.2861 | 2.2604 | 0.1194 | 1.3186 | 0.9252 |
| 22 | 4.3168 | 0.3478 | 41.0884 | 421.5451 | 0.4058 | 1.0970 | 0.1059 | 1.3456 | 1.4050 |
| 23 | 3.7349 | 0.5557 | 38.3712 | 328.2592 | 0.3215 | 1.1687 | 0.1486 | 1.3299 | 1.0219 |
| 24 | 3.7720 | 0.4218 | 18.1263 | 234.9734 | 0.4862 | 1.2907 | 0.1094 | 1.2738 | 1.2038 |
| 25 | 3.3368 | 0.6709 | 40.9749 | 283.3394 | 2.0962 | 0.8535 | 0.0309 | 1.2177 | 1.1289 |
| 26 | 4.4882 | 0.8357 | 43.2176 | 462.2908 | 0.3766 | 2.5657 | 0.1261 | 1.3483 | 0.8950 |
| 27 | 3.5984 | 0.2979 | 27.5130 | 382.8046 | 0.4495 | 2.6922 | 0.0532 | 1.3699 | 1.0935 |
| 28 | 4.0360 | 0.3857 | 32.7295 | 256.3509 | 0.2566 | 1.1344 | 0.2130 | 1.3596 | 0.9652 |
| 29 | 4.4735 | 0.3163 | 12.9593 | 210.2566 | 0.3344 | 1.0248 | 0.0617 | 1.2439 | 0.9968 |
| 30 | 3.4911 | 0.2789 | 26.2751 | 313.6164 | 0.1681 | 0.7068 | 0.1069 | 1.3755 | 0.8381 |
| 31 | 3.6893 | 0.3028 | 36.2170 | 432.7451 | 0.3510 | 1.6458 | 0.0756 | 1.2940 | 1.0812 |
| 32 | 2.6984 | 0.3028 | 31.2771 | 385.1027 | 0.0534 | 1.3677 | 0.1027 | 1.3936 | 0.7285 |
| 33 | 3.5649 | 0.6338 | 28.2493 | 466.6443 | 3.3803 | 0.9230 | 0.0888 | 1.1920 | 1.2520 |
| 34 | 3.5196 | 0.9239 | 25.2215 | 266.7142 | 0.2156 | 1.2712 | 0.0750 | 1.3840 | 1.4124 |
| 35 | 4.2690 | 0.3323 | 26.1959 | 358.3957 | 0.2460 | 1.0211 | 0.0735 | 1.3515 | 1.4216 |
| 36 | 3.8868 | 0.7752 | 29.0456 | 305.1510 | 0.2959 | 0.8071 | 0.0573 | 1.1605 | 1.3796 |
| 37 | 4.1583 | 0.4071 | 39.8754 | 385.5085 | 0.5115 | 1.5924 | 0.0695 | 0.9695 | 1.6188 |
| 38 | 3.5860 | 0.4071 | 22.3318 | 271.0537 | 0.2481 | 1.4146 | 0.0906 | 1.1467 | 1.0037 |
| 39 | 3.4441 | 0.4626 | 37.3521 | 351.2028 | 0.1877 | 1.0058 | 0.1380 | 1.3238 | 1.1157 |
| 40 | 3.1687 | 0.7044 | 36.5145 | 433.5970 | 0.6460 | 1.5237 | 0.0248 | 1.3655 | 1.2129 |
| 41 | 4.4428 | 0.6050 | 41.2989 | 404.6245 | 0.4938 | 0.9895 | 0.0643 | 1.3789 | 1.6094 |
| 42 | 3.1259 | 0.5561 | 28.4553 | 247.0796 | 0.5500 | 1.1184 | 0.1224 | 1.3593 | 1.0721 |
| 43 | 3.2111 | 0.9086 | 42.2977 | 424.7198 | 0.3860 | 2.7086 | 0.1187 | 0.7265 | 1.0253 |
| 44 | 3.8286 | 1.4046 | 41.1128 | 308.2762 | 0.2784 | 1.6006 | 0.1252 | 1.3862 | 1.1716 |
| 45 | 3.2555 | 0.3395 | 28.5837 | 437.5445 | 0.2595 | 0.6743 | 0.1418 | 1.3595 | 0.5319 |
| 46 | 3.4677 | 0.3660 | 29.7889 | 480.8874 | 0.9951 | 1.0527 | 0.0710 | 1.3361 | 0.7104 |
| 47 | 2.6453 | 0.1708 | 30.9941 | 424.0026 | 0.5310 | 1.0258 | 0.0366 | 1.3446 | 0.3335 |
| 48 | 2.8742 | 0.2016 | 20.5063 | 356.9120 | 0.3491 | 1.2539 | 0.0907 | 1.3531 | 1.2900 |
| 49 | 3.0249 | 1.4163 | 24.0416 | 301.2382 | 0.1782 | 1.1097 | 0.1809 | 1.3854 | 0.3429 |
| 50 | 3.1570 | 0.1738 | 34.2594 | 372.6803 | 0.2407 | 0.7734 | 0.1572 | 1.3221 | 0.2175 |
| 51 | 2.7615 | 0.1738 | 29.2670 | 388.3313 | 0.2149 | 0.5678 | 0.0948 | 1.4158 | 0.1332 |
| 52 | 2.5269 | 0.1882 | 31.6429 | 368.0909 | 0.3468 | 0.8758 | 0.1116 | 1.4173 | 0.7748 |
| 53 | 3.2155 | 0.1810 | 39.5915 | 400.0759 | 0.2534 | 1.2618 | 0.1472 | 1.3470 | 0.1753 |
| 54 | 3.1129 | 0.1846 | 27.5642 | 429.4496 | 0.2758 | 1.3527 | 0.1484 | 1.3242 | 0.5350 |
| 55 | 2.9384 | 0.2283 | 21.4078 | 379.0760 | 0.1724 | 1.2959 | 0.0694 | 1.4044 | 0.2018 |
| 56 | 3.1162 | 0.4489 | 38.5061 | 262.3098 | 0.2213 | 0.9881 | 0.1172 | 1.3750 | 0.5679 |
| 57 | 3.0671 | 0.3259 | 35.1918 | 464.3946 | 0.2232 | 0.7990 | 0.1069 | 1.3511 | 0.1103 |
| 58 | 3.0180 | 0.1272 | 33.5844 | 270.0873 | 0.2678 | 1.3287 | 0.0686 | 1.3632 | 0.1006 |
| 59 | 3.2052 | 0.1433 | 11.4043 | 142.2089 | 0.5272 | 0.7024 | 0.1591 | 1.3826 | 1.1248 |
| 60 | 3.1242 | 0.3069 | 34.1949 | 443.1615 | 0.2835 | 1.0129 | 0.1163 | 1.4021 | 0.2098 |
| 61 | 2.7623 | 0.4085 | 34.9352 | 408.0925 | 0.2134 | 1.1039 | 0.0578 | 1.3321 | 0.1386 |
| 62 | 2.8432 | 0.1519 | 36.9290 | 344.4636 | 0.2619 | 2.0577 | 0.0771 | 1.3948 | 0.3894 |

Table 3 (*Contd.*)

| Sample | $^{52}$Cr | $^{59}$Co | $^{63}$Cu | $^{64}$Zn | $^{75}$As | $^{98}$Mo | $^{114}$Cd | $^{200}$Hg | $^{208}$Pb |
|---|---|---|---|---|---|---|---|---|---|
| 63 | 4.1878 | 0.3345 | 9.1977 | 134.4863 | 0.4548 | 0.9307 | 0.1141 | 1.4173 | 0.4110 |
| 64 | 3.1322 | 0.3450 | 26.6805 | 312.8473 | 0.9281 | 0.6405 | 0.1073 | 1.3230 | 0.1347 |
| 65 | 3.1121 | 0.1908 | 31.7398 | 338.2844 | 0.2522 | 1.1128 | 0.0761 | 1.3573 | 0.3616 |
| 66 | 3.4821 | 0.1775 | 32.2059 | 371.2851 | 0.3610 | 0.8052 | 0.0933 | 1.3598 | 0.3240 |
| 67 | 3.1209 | 0.2395 | 40.7115 | 383.6189 | 0.5733 | 1.8932 | 0.0709 | 1.3474 | 0.5612 |
| 68 | 3.7769 | 0.4674 | 36.1355 | 339.5934 | 0.2854 | 1.3273 | 0.0451 | 1.4065 | 0.1853 |
| 69 | 4.1580 | 0.3169 | 27.9955 | 390.1995 | 0.4916 | 1.7607 | 0.0423 | 1.3261 | 0.6607 |
| 70 | 2.8548 | 0.1850 | 20.1241 | 304.9303 | 0.3348 | 0.6640 | 0.0737 | 1.4339 | 0.2511 |
| 71 | 3.0077 | 0.1863 | 35.9813 | 345.2672 | 0.3878 | 1.8668 | 0.0714 | 1.1055 | 0.3811 |
| 72 | 3.9217 | 0.1956 | 22.9370 | 322.7907 | 0.1912 | 1.3454 | 0.1066 | 1.2100 | 0.2553 |
| 73 | 2.6793 | 0.2118 | 16.9680 | 236.1149 | 0.2863 | 0.7125 | 0.0824 | 1.3144 | 0.2406 |
| 74 | 3.1970 | 0.2184 | 10.6198 | 130.4647 | 0.2410 | 0.8951 | 0.0945 | 1.4310 | 0.1964 |
| 75 | 3.0702 | 0.2142 | 28.7941 | 421.1496 | 0.2192 | 0.6954 | 0.1363 | 1.4209 | 0.2302 |
| 76 | 2.4707 | 0.2075 | 29.4575 | 381.1963 | 0.0830 | 1.3390 | 0.1419 | 1.4339 | 0.1133 |
| 77 | 2.8153 | 0.4269 | 20.0577 | 174.4690 | 0.1381 | 1.0109 | 0.1818 | 1.3958 | 0.1843 |
| 78 | 3.0987 | 0.4264 | 25.4943 | 376.8879 | 0.2128 | 1.0030 | 0.0781 | 1.3944 | 0.2394 |
| 79 | 2.2964 | 0.3151 | 31.2618 | 385.9180 | 0.6843 | 1.1143 | 0.0334 | 1.3756 | 0.3735 |
| 80 | 3.2164 | 0.2355 | 35.9985 | 444.2483 | 0.2589 | 0.6743 | 0.1083 | 1.3946 | 1.2845 |
| 81 | 2.6270 | 0.0857 | 17.0701 | 219.6903 | 0.1843 | 1.0487 | 0.1372 | 1.4611 | 0.6150 |
| LOD | 0.00003 | 0.00001 | 0.00001 | 0.00003 | 0.00005 | 0.00002 | 0.00003 | 0.00004 | 0.00004 |
| LOQ | 0.0001 | 0.00005 | 0.00005 | 0.00005 | 0.0001 | 0.00005 | 0.00005 | 0.00008 | 0.00008 |
| Sample | $^{52}$Cr | $^{59}$Co | $^{63}$Cu | $^{64}$Zn | $^{75}$As | $^{98}$Mo | $^{114}$Cd | $^{200}$Hg | $^{208}$Pb |

availability of pet food products in the UAE compared to Lebanon. A notable difference is observed in the type of pet food available in both countries. In Lebanon, dry pet food was more prevalent, comprising 70.7% of the total samples collected, while only 29.3% were wet food. Conversely, the UAE showed the opposite trend, with 76.9% of samples being wet food and only 23.1% dry food. This suggests different consumer preferences or market availability in each country, potentially influenced by factors such as climate, pet nutrition trends, or import regulations. Across both countries, cat food dominated the market, accounting for 75% of the total samples. This trend is more pronounced in the UAE, where cat food represents 80.2% of samples, compared to 66.7% in Lebanon. Dog food is less common overall, with 33.3% of samples in Lebanon and only 19.8% in the UAE. This could reflect pet ownership trends, with cats being more popular due to their lower maintenance requirements, particularly in urban environments. The origin of pet food products varies significantly between the two countries. In Lebanon, pet food is sourced from a diverse range of countries, including Italy (17.3%), the Czech Republic (13.3%), and Brazil (9.3%). In contrast, the UAE imports a large proportion of its pet food from Thailand (37.2%), followed by the USA (18.2%) and Germany (8.3%). When grouping pet food sources based on economic classification, 65.3% of all SKUs originate from developed countries, while 34.7% come from developing countries. Lebanon appears to rely more on imports from developed countries, with 69.3% of its SKUs coming from these nations, whereas the UAE has a slightly lower proportion at 62.8%.

The quantification of 9 metals (Cr, Co, Cu, Zn, As, Mo, Cd, Hg, and Pb) was conducted using ICP-MS as reported in Table 3 for dry food and Table 4 for wet food. The datasets present concentrations of toxic metals in dry and wet food samples, enabling an assessment of potential health risks to pets. The highest concentrations detected correspond to Zn, ranging from 134 to 480 mg kg$^{-1}$. Copper was also prevalent, with concentrations varying between 9 and 43 mg kg$^{-1}$. Chromium exhibited moderate variation, generally spanning from 2.1 to 4.5 mg kg$^{-1}$. In contrast, Mo, Co, Cd, and Hg were present at significantly lower concentrations. The toxic elements of concern, Pb and As, were detected at variable levels, occasionally exceeding 3 mg kg$^{-1}$ for Pb and 2 mg kg$^{-1}$ for As. Table 5 presents the statistical summary of elemental concentrations, including the mean, standard deviation, median, and interquartile range (IQR) limits for various elements. The mean concentration of Cr is 2.745 $\pm$ 0.923 mg kg$^{-1}$, indicating moderate variability. The median (2.779 mg kg$^{-1}$) is close to the mean, suggesting a relatively symmetric distribution. The IQR (2.126–3.390 mg kg$^{-1}$) indicates that most samples fall within this range, with some outliers likely present beyond these limits. On the other hand, Co exhibits a low mean concentration of 0.298 mg kg$^{-1}$ and a high standard deviation (0.493 mg kg$^{-1}$), indicating significant variability. The median (0.142 mg kg$^{-1}$) is lower than the mean, suggesting a right-skewed distribution, while the IQR (0.077–0.317 mg kg$^{-1}$) captures a narrow range, highlighting that a few higher values may influence the overall distribution. Cu has a mean concentration of 15.375 mg kg$^{-1}$, with a relatively high standard deviation (13.759 mg kg$^{-1}$), suggesting strong variability. The median (9.227 mg kg$^{-1}$) is notably lower than the mean, indicating a right-skewed distribution with higher extreme values, while the IQR (3.545–28.689 mg kg$^{-1}$) demonstrates a broad range, reinforcing the

Table 4 Detected concentrations of toxic metals (mg kg$^{-1}$) in wet food (LOD: limit of detection, LOQ: limit of quantification). Samples 1 to 73 are originating from UAE while samples from 74 to 86 are originating from Lebanon

| Sample | $^{52}$Cr | $^{59}$Co | $^{63}$Cu | $^{64}$Zn | $^{75}$As | $^{98}$Mo | $^{114}$Cd | $^{200}$Hg | $^{208}$Pb |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.2260 | 0.0640 | 3.6766 | 26.7583 | 0.2678 | 0.6590 | 0.1538 | 0.6363 | 1.1102 |
| 2 | 2.5616 | 0.0192 | 3.7128 | 82.9727 | 0.0625 | 0.5168 | 0.1546 | 0.7643 | 0.3979 |
| 3 | 2.9383 | 0.3389 | 5.5668 | 171.4451 | 0.0352 | 1.0408 | 0.1534 | 0.3696 | 0.7494 |
| 4 | 2.9499 | 0.4548 | 5.7368 | 53.8310 | 0.0511 | 0.7867 | 0.1512 | 0.4436 | 1.5367 |
| 5 | 2.8309 | 0.3155 | 3.8989 | 23.0570 | 0.0538 | 0.8225 | 0.1503 | 0.6903 | 1.0178 |
| 6 | 3.1712 | 0.2809 | 4.0404 | 31.0603 | 0.1031 | 0.7429 | 0.1489 | 0.8027 | 0.9379 |
| 7 | 2.8872 | 0.2092 | 4.0352 | 32.7076 | 0.0245 | 0.8980 | 0.0990 | 0.9670 | 0.6374 |
| 8 | 2.4959 | 0.1320 | 4.6402 | 30.5319 | 0.0156 | 0.6491 | 0.1488 | 0.9760 | 0.4293 |
| 9 | 2.9114 | 0.1402 | 2.9214 | 33.3010 | 0.0377 | 0.7042 | 0.1555 | 0.9457 | 0.5344 |
| 10 | 3.4899 | 0.1293 | 2.4231 | 28.7802 | 0.0152 | 0.6236 | 0.1522 | 1.0154 | 0.4462 |
| 11 | 2.6350 | 0.1605 | 2.1553 | 22.4707 | 0.0684 | 0.6838 | 0.1557 | 0.6261 | 0.6051 |
| 12 | 2.5305 | 0.1743 | 3.3864 | 36.1106 | 0.1593 | 0.8135 | 0.1487 | 1.0564 | 0.5029 |
| 13 | 2.8378 | 0.3270 | 2.6786 | 20.9238 | 0.0232 | 0.5888 | 0.1532 | 0.9098 | 0.9898 |
| 14 | 2.7956 | 0.2594 | 5.7016 | 31.6302 | 0.0252 | 0.6068 | 0.1528 | 0.9476 | 0.8584 |
| 15 | 2.7603 | 0.0928 | 11.8627 | 79.6314 | 0.0644 | 0.5574 | 0.1503 | 1.1527 | 0.3478 |
| 16 | 2.7055 | 0.0612 | 11.8733 | 78.3736 | 0.0842 | 0.4521 | 0.1512 | 0.9897 | 0.4423 |
| 17 | 3.1271 | 0.1655 | 7.3861 | 83.8694 | 0.0840 | 0.4642 | 0.1488 | 1.1182 | 0.3871 |
| 18 | 3.6541 | 0.0996 | 11.4402 | 83.6891 | 0.0241 | 0.3361 | 0.1506 | 1.0809 | 0.3162 |
| 19 | 2.5468 | 0.0926 | 17.1440 | 17.0130 | 0.0015 | 0.3329 | 0.1507 | 0.7339 | 0.5628 |
| 20 | 2.8432 | 0.0643 | 9.8341 | 12.9254 | 0.0030 | 0.2635 | 0.1558 | 1.0805 | 0.5743 |
| 21 | 2.7261 | 0.0813 | 12.1031 | 24.2660 | 0.0092 | 0.2895 | 0.1557 | 1.1633 | 0.3098 |
| 22 | 2.4775 | 0.0733 | 2.7812 | 32.2621 | 0.0492 | 0.3244 | 0.1537 | 1.1256 | 1.1374 |
| 23 | 2.9331 | 0.0822 | 3.0567 | 31.7790 | 0.0128 | 0.2488 | 0.1527 | 1.2428 | 0.6933 |
| 24 | 2.3575 | 0.0505 | 2.3843 | 19.2102 | 0.0286 | 0.2464 | 0.1480 | 1.3442 | 0.6870 |
| 25 | 2.6475 | 0.0894 | 4.7269 | 39.9820 | 0.0308 | 0.3277 | 0.1534 | 1.2012 | 0.3591 |
| 26 | 2.2040 | 0.0900 | 10.2465 | 39.9652 | 0.0081 | 0.4567 | 0.1469 | 1.0863 | 0.6356 |
| 27 | 2.5102 | 0.1435 | 5.2673 | 73.8041 | 0.0529 | 1.0890 | 0.1530 | 1.2937 | 0.6477 |
| 28 | 2.7458 | 0.1152 | 2.6298 | 35.5306 | 0.1329 | 1.2286 | 0.1526 | 0.5216 | 0.4351 |
| 29 | 2.4811 | 0.1214 | 3.2629 | 27.5930 | 0.0091 | 1.1368 | 0.1520 | 1.3229 | 0.5583 |
| 30 | 1.8960 | 0.0496 | 2.1785 | 19.8714 | 0.0296 | 0.9303 | 0.1524 | 1.3841 | 0.4232 |
| 31 | 3.4013 | 0.2004 | 2.9962 | 22.1459 | 0.0177 | 1.4884 | 0.1538 | 0.9143 | 0.3366 |
| 32 | 2.6916 | 0.0840 | 3.2501 | 53.3640 | 0.0267 | 0.4087 | 0.1523 | 1.3238 | 0.3201 |
| 33 | 2.2847 | 0.0838 | 2.6753 | 23.8856 | 0.0246 | 1.2549 | 0.1552 | 0.2484 | 0.6060 |
| 34 | 2.4602 | 0.0746 | 5.3945 | 27.0681 | 0.0045 | 0.7720 | 0.1531 | 1.3002 | 0.4911 |
| 35 | 2.5231 | 0.1057 | 11.7666 | 20.2812 | 0.0376 | 1.5725 | 0.1560 | 1.2416 | 0.5681 |
| 36 | 2.5676 | 0.0846 | 11.2066 | 19.3511 | 0.0128 | 0.3209 | 0.1533 | 1.2374 | 0.8892 |
| 37 | 2.5858 | 0.1192 | 3.6154 | 18.4977 | 0.0223 | 1.2419 | 0.1548 | 1.3427 | 0.7274 |
| 38 | 2.3250 | 0.0840 | 10.5318 | 21.9844 | 0.0192 | 0.9343 | 0.1559 | 1.3055 | 0.6173 |
| 39 | 1.6779 | 0.1116 | 5.7664 | 55.5393 | 0.0546 | 0.7187 | 0.1556 | 1.3263 | 0.2949 |
| 40 | 1.6591 | 0.0624 | 5.1705 | 35.3875 | 0.0077 | 0.3174 | 0.1384 | 1.3831 | 0.2200 |
| 41 | 1.5784 | 0.0765 | 11.8804 | 88.1354 | 0.0077 | 0.6428 | 0.1519 | 1.3564 | 0.2404 |
| 42 | 1.7618 | 0.0606 | 9.2910 | 146.1929 | 0.0046 | 0.7253 | 0.1537 | 1.2941 | 0.2318 |
| 43 | 1.6664 | 0.0548 | 4.4734 | 28.2502 | 0.0016 | 0.6444 | 0.1514 | 1.3919 | 0.2049 |
| 44 | 1.6157 | 0.0571 | 5.4101 | 26.7473 | 0.0151 | 0.6448 | 0.1518 | 1.3604 | 0.2327 |
| 45 | 1.5716 | 0.0797 | 4.9735 | 36.5622 | 0.0116 | 0.5421 | 0.1535 | 1.4081 | 0.2416 |
| 46 | 1.7723 | 0.0514 | 3.8619 | 24.7406 | 0.0008 | 0.7296 | 0.1562 | 1.3449 | 0.2023 |
| 47 | 1.7141 | 0.0602 | 11.4842 | 67.4259 | 0.0061 | 0.9239 | 0.1415 | 1.3547 | 0.2229 |
| 48 | 1.6484 | 0.0651 | 9.5664 | 60.3120 | 0.0082 | 0.7533 | 0.1397 | 1.4149 | 0.2185 |
| 49 | 1.8345 | 0.0677 | 4.1716 | 40.6453 | 0.0386 | 0.7814 | 0.1527 | 1.4273 | 0.2455 |
| 50 | 1.5942 | 0.0667 | 14.8429 | 62.3693 | 0.0514 | 0.5601 | 0.1528 | 0.5670 | 0.2363 |
| 51 | 1.7685 | 0.0627 | 3.3360 | 16.9146 | 0.0509 | 0.5599 | 0.1551 | 1.2925 | 0.2301 |
| 52 | 1.6980 | 0.0545 | 4.0448 | 54.0095 | 0.1703 | 0.5599 | 0.1544 | 1.2841 | 0.2054 |
| 53 | 1.5554 | 0.0490 | 6.2690 | 40.1393 | 0.1330 | 0.5954 | 0.1527 | 1.2972 | 0.1986 |
| 54 | 1.6294 | 0.0479 | 3.4236 | 35.6963 | 0.1642 | 0.7351 | 0.1482 | 1.2224 | 0.1982 |
| 55 | 1.9653 | 0.1026 | 3.0451 | 26.6453 | 0.0175 | 0.6274 | 0.1529 | 1.3752 | 0.3180 |
| 56 | 1.7134 | 0.0726 | 2.6063 | 28.7816 | 0.0054 | 0.3851 | 0.1508 | 0.6875 | 0.3055 |
| 57 | 1.8565 | 0.0900 | 3.3883 | 52.2816 | 0.0107 | 0.5746 | 0.1547 | 1.3777 | 0.2827 |
| 58 | 2.3019 | 0.1248 | 11.0552 | 81.7687 | 0.0735 | 0.6763 | 0.1524 | 1.3050 | 0.4066 |
| 59 | 2.2966 | 0.1307 | 3.0012 | 10.5200 | 0.6428 | 0.2627 | 0.1525 | 1.0637 | 0.4671 |
| 60 | 2.7397 | 0.1303 | 0.9331 | 12.8142 | −0.0016 | 0.4475 | 0.1576 | 1.7137 | 0.4958 |
| 61 | 3.0004 | 0.1989 | 4.0430 | 41.6669 | 0.0960 | 0.9447 | 0.1546 | 1.3335 | 0.5666 |
| 62 | 3.7006 | 0.2904 | 9.2558 | 133.0699 | 0.1219 | 0.6723 | 0.1499 | 1.3730 | 0.6614 |

 

Table 4 (*Contd.*)

| Sample | $^{52}$Cr | $^{59}$Co | $^{63}$Cu | $^{64}$Zn | $^{75}$As | $^{98}$Mo | $^{114}$Cd | $^{200}$Hg | $^{208}$Pb |
|---|---|---|---|---|---|---|---|---|---|
| 63 | 4.5471 | 0.1521 | 3.2337 | 52.5852 | 0.0285 | 0.3138 | 0.1453 | 1.4411 | 0.5890 |
| 64 | 3.5509 | 0.1282 | 4.3282 | 39.0759 | 0.0483 | 0.2256 | 0.1457 | 1.4823 | 0.5855 |
| 65 | 3.7202 | 0.2656 | 7.4279 | 51.3903 | 0.0923 | 0.3337 | 0.1440 | 1.4718 | 0.6719 |
| 66 | 3.6525 | 0.1215 | 10.4711 | 52.0966 | 0.0054 | 0.8190 | 0.1406 | 1.4467 | 0.5835 |
| 67 | 3.6211 | 0.1228 | 3.7479 | 48.0914 | 0.0324 | 0.2785 | 0.1469 | 1.2716 | 0.7608 |
| 68 | 3.6485 | 0.1202 | 7.1069 | 48.5835 | 0.0024 | 0.3216 | 0.1436 | 1.4597 | 0.5767 |
| 69 | 3.6348 | 0.1169 | 4.9516 | 32.9692 | 0.0459 | 0.2572 | 0.1456 | 1.4744 | 0.5526 |
| 70 | 3.5761 | 0.1212 | 5.1694 | 44.9644 | 0.0332 | 0.2699 | 0.1476 | 1.4937 | 0.5591 |
| 71 | 4.5686 | 0.3721 | 3.0374 | 39.3322 | 0.1159 | 0.2508 | 0.1420 | 1.4960 | 1.1223 |
| 72 | 6.4277 | 0.1290 | 4.0197 | 52.5880 | 0.0207 | 0.3165 | 0.1455 | 1.4957 | 0.5677 |
| 73 | 3.3785 | 0.1370 | 5.3736 | 38.5197 | 0.4708 | 0.2119 | 0.1437 | 1.3059 | 0.6201 |
| 74 | 3.4349 | 0.1391 | 4.9335 | 40.3254 | 0.0269 | 0.1973 | 0.1463 | 1.6829 | 0.6276 |
| 75 | 0.1002 | 0.0848 | 0.6093 | 7.4828 | 0.0008 | 0.8579 | 0.1581 | 1.8876 | 0.2706 |
| 76 | 1.9508 | 0.1277 | 4.0697 | 56.3135 | 0.2889 | 0.2082 | 0.1503 | 1.3213 | 0.3009 |
| 77 | 2.0794 | 0.0869 | 3.5367 | 36.4961 | 0.0314 | 0.2803 | 0.1549 | 1.4195 | 0.2785 |
| 78 | 2.2017 | 0.0776 | 6.2560 | 24.8748 | 0.0169 | 0.3641 | 0.1544 | 1.5049 | 0.2608 |
| 79 | 2.1721 | 0.0661 | 5.1200 | 29.6867 | 0.0128 | 0.3777 | 0.1483 | 0.8340 | 0.2722 |
| 80 | 4.0024 | 0.1345 | 3.9516 | 53.8765 | 0.0273 | 0.4968 | 0.1527 | 1.3705 | 0.3375 |
| 81 | 2.5577 | 0.0782 | 8.1353 | 72.3260 | 0.2005 | 0.3330 | 0.1460 | 1.4261 | 0.2648 |
| 82 | 3.1172 | 0.0969 | 4.7641 | 54.9373 | 0.1489 | 0.6945 | 0.2765 | 0.3440 | 0.3531 |
| 83 | 2.2774 | 0.0799 | 4.5621 | 14.9112 | 0.0735 | 0.4996 | 0.2668 | 0.8019 | 0.3308 |
| 84 | 3.6330 | 0.0976 | 2.4932 | 34.0657 | 0.0410 | 0.5374 | 0.2726 | 0.7794 | 0.3504 |
| 85 | 2.5344 | 0.0825 | 2.1806 | 14.4489 | 0.0247 | 0.2810 | 0.2766 | 0.8028 | 0.3427 |
| 86 | 2.5915 | 0.1006 | 7.4121 | 38.3985 | 0.0605 | 0.3111 | 0.2763 | 0.7831 | 0.3475 |
| LOD | 0.00003 | 0.00001 | 0.00001 | 0.00003 | 0.00005 | 0.00002 | 0.00003 | 0.00004 | 0.00004 |
| LOQ | 0.0001 | 0.00005 | 0.00005 | 0.00005 | 0.0001 | 0.00005 | 0.00005 | 0.00008 | 0.00008 |
| Sample | $^{52}$Cr | $^{59}$Co | $^{63}$Cu | $^{64}$Zn | $^{75}$As | $^{98}$Mo | $^{114}$Cd | $^{200}$Hg | $^{208}$Pb |

presence of samples with significantly higher Cu concentrations. Zn exhibits the highest mean concentration among the analyzed elements (165.837 mg kg$^{-1}$), with a large standard deviation (164.404 mg kg$^{-1}$), indicating substantial variability. The median concentration (55.926 mg kg$^{-1}$) is markedly lower than the mean, suggesting a pronounced right-skewed distribution, likely influenced by a subset of exceptionally high values. The interquartile range (IQR) of 27.003–343.637 mg kg$^{-1}$ further confirms the broad dispersion of Zn concentrations across samples. As has a low mean concentration of 0.193 ± 0.324 mg kg$^{-1}$, reflecting moderate variability. The median value (0.094 mg kg$^{-1}$) is lower than the mean, suggesting a right-skewed distribution. The IQR (0.025–0.259 mg kg$^{-1}$) for As indicates that most concentrations are relatively low, although certain samples exhibit elevated levels. On the other hand, Mo has a mean concentration of 0.819 ± 0.567 mg kg$^{-1}$, suggesting moderate variation. The median concentration (0.716 mg kg$^{-1}$) closely approximates the mean, indicating a near-symmetric distribution. The IQR (0.335–1.116 mg kg$^{-1}$) suggests that Mo concentrations are largely contained within this interval, with minimal extreme values. Cd presents a mean concentration of 0.216 mg kg$^{-1}$ and a low standard deviation (0.219 mg kg$^{-1}$), indicating limited variability. The median (0.149 mg kg$^{-1}$) is slightly lower than the mean, suggesting a mild right-skewed distribution. The narrow IQR (0.112–0.155 mg kg$^{-1}$) indicates that Cd concentrations are relatively consistent across samples, with few outliers. Hg exhibits a mean concentration of 1.213 mg kg$^{-1}$, with a low standard deviation (0.245 mg kg$^{-1}$), reflecting minimal variation. The median value (1.293 mg kg$^{-1}$) is marginally higher than the mean, suggesting a slight left-skewed distribution. The IQR (1.144–1.370 mg kg$^{-1}$)

Table 5 Mean, standard deviation, median, and IQR limits of toxic metals (mg kg$^{-1}$) in dry and wet food

| | | | | | |
|---|---|---|---|---|---|
| $^{52}$Cr | Mean | 2.745 | $^{98}$Mo | Mean | 0.819 |
| | Standard deviation | 0.923 | | Standard deviation | 0.567 |
| | Median | 2.779 | | Median | 0.716 |
| | IQR lower limit | 2.126 | | IQR lower limit | 0.335 |
| | IQR upper limit | 3.390 | | IQR upper limit | 1.116 |
| $^{59}$Co | Mean | 0.298 | $^{114}$Cd | Mean | 0.216 |
| | Standard deviation | 0.493 | | Standard deviation | 0.219 |
| | Median | 0.142 | | Median | 0.149 |
| | IQR lower limit | 0.077 | | IQR lower limit | 0.112 |
| | IQR upper limit | 0.317 | | IQR upper limit | 0.155 |
| $^{63}$Cu | Mean | 15.375 | $^{200}$Hg | Mean | 1.213 |
| | Standard deviation | 13.759 | | Standard deviation | 0.245 |
| | Median | 9.227 | | Median | 1.293 |
| | IQR lower limit | 3.545 | | IQR lower limit | 1.144 |
| | IQR upper limit | 28.689 | | IQR upper limit | 1.370 |
| $^{64}$Zn | Mean | 165.837 | $^{208}$Pb | Mean | 0.653 |
| | Standard deviation | 164.404 | | Standard deviation | 0.684 |
| | Median | 55.926 | | Median | 0.439 |
| | IQR lower limit | 27.003 | | IQR lower limit | 0.244 |
| | IQR upper limit | 343.637 | | IQR upper limit | 0.892 |
| $^{75}$As | Mean | 0.193 | | | |
| | Standard deviation | 0.324 | | | |
| | Median | 0.094 | | | |
| | IQR lower limit | 0.025 | | | |
| | IQR upper limit | 0.259 | | | |

is relatively narrow, indicating a stable Hg concentration across samples. Similarly, Pb has a mean concentration of 0.653 ± 0.684 mg kg$^{-1}$, suggesting moderate variability. The median (0.439 mg kg$^{-1}$) is lower than the mean, indicating a right-skewed distribution. The IQR (0.244–0.892 mg kg$^{-1}$) suggests that while most Pb concentrations fall within this range, occasional elevated values contribute to the overall variation.

Among the studied elements, Zn and Cu exhibit the highest mean concentrations, with substantial variation, implying diverse sources or high environmental mobility. In contrast, Hg shows minimal variation, suggesting a stable presence across samples. Pb, Co, and As display right-skewed distributions, indicating occasional elevated concentrations, possibly linked to localized contamination. Cd demonstrates the least variability, suggesting a relatively uniform distribution. Overall, the results indicate a heterogeneous distribution of metal concentrations, with Zn, Cu, and Pb exhibiting significant variability, whereas Hg and Cd remain more consistent. These findings provide valuable insights into potential contamination sources and environmental processes influencing metal accumulation in the studied samples. Table 6 represents a comparative analysis of toxic metal concentrations across different conditions. A significant difference ($p$ < 0.001) is observed between dry and wet samples across all analyzed metals. Dry samples exhibit notably higher concentrations for most elements, particularly Cu (30.302 mg kg$^{-1}$ *vs.* 4.861 mg kg$^{-1}$), Zn (350.223 mg kg$^{-1}$ *vs.* 35.965 mg kg$^{-1}$), and Pb (0.981 mg kg$^{-1}$ *vs.* 0.421 mg kg$^{-1}$). The substantial reduction in metal concentrations in wet samples suggests dilution effects in the presence of moisture or possible leaching of metals. The high standard deviations in dry samples indicate greater variability in contamination levels, possibly due to localized deposition or accumulation over time. Water content plays a critical role in the apparent differences in metal concentrations observed between dry and wet pet food. These concentrations are typically reported on a dry weight basis to standardize the comparison across food types with different moisture levels. When metal concentrations are normalized to a dry weight basis, this correction compensates for the dilution effect of water in wet food, enabling a more accurate assessment of the contaminant burden. However, despite this normalization, dry pet foods often exhibit higher apparent concentrations of metals. This is not merely a result of standardization but can be attributed to the inherently lower moisture content in dry foods, which causes any residual metals or contaminants present to become more concentrated per unit mass. Additionally, the manufacturing process of dry pet food often involves the use of mineral-rich additives, animal by-products, and rendered meals

Table 6 Comparative analysis of toxic metal concentrations (mg kg$^{-1}$) across different conditions

| | Mean | SD | Median | IQR lower limit | IQR upper limit | Mean | SD | Median | IQR lower limit | IQR upper limit | Means $p$-value | Medians $p$-value |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dry** | | | | | | **Wet** | | | | | | |
| Cr | 3.299 | 0.584 | 3.169 | 2.874 | 3.689 | 2.370 | 0.926 | 2.302 | 1.714 | 2.887 | <0.001 | <0.001 |
| Co | 0.568 | 0.677 | 0.340 | 0.218 | 0.556 | 0.109 | 0.075 | 0.084 | 0.062 | 0.129 | <0.001 | <0.001 |
| Cu | 30.302 | 7.834 | 31.277 | 26.275 | 35.981 | 4.861 | 3.300 | 3.899 | 2.606 | 5.567 | <0.001 | <0.001 |
| Zn | 350.223 | 81.282 | 372.161 | 302.756 | 408.093 | 35.965 | 20.632 | 30.532 | 20.833 | 48.583 | <0.001 | <0.001 |
| As | 0.381 | 0.428 | 0.268 | 0.213 | 0.423 | 0.060 | 0.090 | 0.030 | 0.014 | 0.064 | <0.001 | <0.001 |
| Mo | 1.280 | 0.527 | 1.142 | 0.994 | 1.412 | 0.495 | 0.314 | 0.409 | 0.251 | 0.684 | <0.001 | <0.001 |
| Cd | 0.102 | 0.039 | 0.107 | 0.074 | 0.130 | 0.296 | 0.251 | 0.153 | 0.150 | 0.276 | <0.001 | <0.001 |
| Hg | 1.291 | 0.141 | 1.345 | 1.244 | 1.379 | 1.158 | 0.285 | 1.169 | 1.081 | 1.345 | <0.001 | <0.001 |
| Pb | 0.981 | 0.927 | 0.901 | 0.343 | 1.204 | 0.421 | 0.258 | 0.331 | 0.236 | 0.574 | <0.001 | <0.001 |
| **Cat** | | | | | | **Dog** | | | | | | |
| Cr | 2.603 | 0.924 | 2.592 | 1.817 | 3.256 | 3.206 | 0.764 | 3.089 | 2.815 | 3.551 | <0.001 | <0.001 |
| Co | 0.258 | 0.408 | 0.112 | 0.065 | 0.298 | 0.419 | 0.678 | 0.236 | 0.178 | 0.345 | 0.121 | <0.001 |
| Cu | 13.217 | 13.425 | 5.394 | 3.001 | 26.275 | 21.849 | 12.797 | 25.494 | 9.198 | 33.584 | <0.001 | <0.001 |
| Zn | 136.587 | 157.461 | 40.139 | 24.266 | 298.886 | 253.587 | 154.625 | 310.787 | 56.313 | 383.619 | <0.001 | <0.001 |
| As | 0.175 | 0.355 | 0.058 | 0.018 | 0.235 | 0.247 | 0.194 | 0.213 | 0.105 | 0.289 | 0.175 | <0.001 |
| Mo | 0.766 | 0.593 | 0.643 | 0.321 | 1.097 | 0.979 | 0.449 | 0.994 | 0.695 | 1.327 | 0.022 | 0.001 |
| Cd | 0.251 | 0.239 | 0.153 | 0.138 | 0.158 | 0.112 | 0.037 | 0.112 | 0.078 | 0.145 | <0.001 | <0.001 |
| Hg | 1.188 | 0.251 | 1.224 | 1.135 | 1.353 | 1.289 | 0.208 | 1.357 | 1.271 | 1.406 | 0.006 | <0.001 |
| Pb | 0.595 | 0.497 | 0.423 | 0.242 | 0.889 | 0.827 | 1.054 | 0.567 | 0.251 | 0.907 | 0.039 | 0.552 |
| **Developed country** | | | | | | **Developing country** | | | | | | |
| Cr | 2.850 | 0.972 | 2.851 | 2.203 | 3.505 | 2.573 | 0.799 | 2.631 | 1.738 | 3.189 | 0.045 | 0.035 |
| Co | 0.272 | 0.409 | 0.152 | 0.079 | 0.326 | 0.348 | 0.620 | 0.128 | 0.075 | 0.292 | 0.365 | 0.451 |
| Cu | 15.375 | 13.851 | 8.667 | 3.480 | 28.689 | 15.374 | 13.685 | 9.911 | 3.661 | 28.878 | 0.999 | 0.983 |
| Zn | 165.203 | 163.411 | 58.313 | 28.469 | 338.939 | 167.030 | 167.472 | 54.774 | 26.293 | 364.099 | 0.941 | 0.828 |
| As | 0.207 | 0.376 | 0.088 | 0.026 | 0.265 | 0.167 | 0.192 | 0.117 | 0.021 | 0.238 | 0.42 | 0.608 |
| Mo | 0.782 | 0.530 | 0.699 | 0.330 | 1.093 | 0.889 | 0.629 | 0.773 | 0.378 | 1.248 | 0.207 | 0.261 |
| Cd | 0.209 | 0.208 | 0.149 | 0.108 | 0.155 | 0.230 | 0.232 | 0.152 | 0.127 | 0.156 | 0.523 | 0.231 |
| Hg | 1.203 | 0.259 | 1.277 | 1.138 | 1.374 | 1.232 | 0.215 | 1.295 | 1.156 | 1.361 | 0.434 | 0.743 |
| Pb | 0.674 | 0.661 | 0.533 | 0.260 | 0.954 | 0.612 | 0.729 | 0.358 | 0.232 | 0.710 | 0.548 | 0.119 |

 

that may contribute to elevated metal content. As a result, even though comparisons are made on a dry weight basis, dry pet food can exhibit higher levels of certain metals due to both compositional and processing factors.

Notably, Cd is the only element that follows an inverse trend, showing higher concentrations in wet samples (0.296 mg kg$^{-1}$ *vs.* 0.102 mg kg$^{-1}$). This may indicate that Cd is more soluble in aqueous environments, leading to higher mobility and retention in wet conditions. When comparing cat and dog food, significant differences ($p < 0.001$) are noted for Cu, Zn, Cd, and Hg, while Co and As show mixed statistical significance. Zn concentrations are significantly higher in dog food (253.587 mg kg$^{-1}$) than in cat food (136.587 mg kg$^{-1}$), with a wider interquartile range in dogs, suggesting greater variability in Zn exposure. Similarly, Cu levels are higher in dog food (21.849 mg kg$^{-1}$) compared to cat food (13.217 mg kg$^{-1}$), indicating potential differences in dietary intake, environmental exposure, or metabolic processing. Interestingly, Cd exhibits the opposite pattern, with higher mean concentrations in cats (0.251 mg kg$^{-1}$) compared to dogs (0.112 mg kg$^{-1}$). This difference may be linked to dietary or environmental factors influencing Cd accumulation. Hg levels are also significantly different, being slightly higher in dog food, although both groups exhibit relatively stable distributions. Pb concentrations are moderately higher in dogs (0.827 mg kg$^{-1}$) than in cats (0.595 mg kg$^{-1}$), but the difference is not statistically significant ($p = 0.039$ for means, $p = 0.552$ for medians), suggesting that variations in Pb exposure may be more influenced by individual cases rather than group-wide trends.

The assessment between developed and developing countries of origin reveals minor differences in metal concentrations, with no significant variations in Cu, Zn, As, Mo, Cd, Hg, or Pb. Cr shows a small but statistically significant difference ($p = 0.045$ for means, $p = 0.035$ for medians), being slightly higher in developed countries (2.850 mg kg$^{-1}$) compared to developing countries (2.573 mg kg$^{-1}$). This may be linked to industrial sources or possible contamination in developed areas. Despite small differences, the lack of statistical significance for most elements suggests that metal exposure levels are relatively similar across regions. This could indicate globalized contamination sources, uniform regulatory measures, or widespread environmental persistence of these metals. In summary, metal concentrations vary significantly across different conditions. Dry samples exhibit higher metal accumulation, while wet samples reflect transient contamination influenced by solubility and leaching. Differences in Zn, Cu, and Cd levels between cat and dog food suggest variations in exposure pathways, metabolism, or diet. Minimal statistical differences between

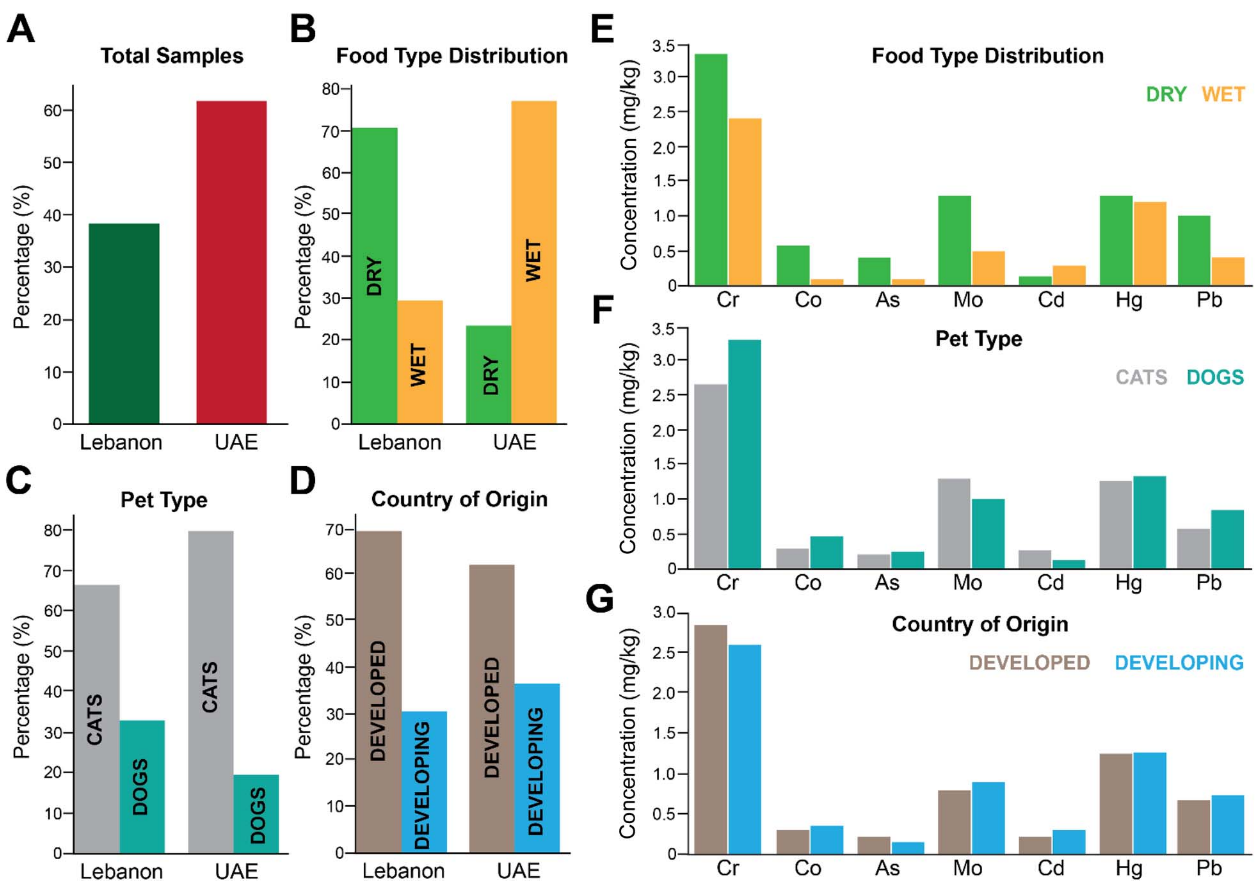


Fig. 1 Distribution of toxic metals in pet food samples categorized by food type, pet type, and country of origin. (A–D) Sample distribution across countries, food types (dry *vs.* wet), pet types (cats *vs.* dogs), and country of origin (developed *vs.* developing). (E–G) Average metal concentrations (in mg kg$^{-1}$) for Cr, Co, As, Mo, Cd, Hg, and Pb across (E) food type, (F) pet type, and (G) country of origin.

developed and developing countries of origin indicate a globalized pattern of metal contamination, with Cr being the only element showing significant variation. Notably, Cd is more concentrated in wet samples, and Hg demonstrates low variability, highlighting distinct environmental behaviors of these metals.

Fig. 1 reports the results that show notable disparities in toxic metal concentrations across pet food samples based on food type, pet type, and country of origin. The total sample distribution shows that the UAE contributed 61.7% of the samples, while Lebanon accounted for 38.3%. In terms of food type, Lebanon had a higher proportion of dry food samples (70.7%), while the UAE predominantly had wet food samples (76.9%). Both countries had more cat food samples, with the UAE having a slightly higher percentage (80.2% for cats compared to 66.7% in Lebanon). Most products in both countries came from developed countries, with Lebanon at 69.3% and the UAE at 62.8%, although the UAE had a higher proportion of products from developing countries. In terms of metal concentrations, dry food consistently exhibited higher levels of all measured metals (Cr, Co, As, Mo, Cd, Hg, Pb) compared to wet food. Dog food generally showed higher average concentrations of most metals, particularly Mo, Hg, and Pb, while cat food had significantly higher levels of Cd, suggesting potential ingredient differences. Pet food from developed countries had slightly higher levels of Cr, As, Hg, and Pb, while pet food from developing countries showed slightly higher levels of Co, Mo, and Cd. Overall, dry food exhibited higher levels of Cr, Co, As, Mo, and Pb, and dog food had higher metal concentrations on average. The differences between products from developed and developing countries were small but still noticeable for certain metals like Mo and Cd. These findings highlight the need for improved monitoring, stricter quality control, and clearer labeling of pet food products to minimize potential health risks for companion animals.

The analysis of toxic metals in pet food reveals concerning levels for several elements when compared to international safety standards (Table 7). Cr showed a mean concentration of 2.75 mg kg$^{-1}$, exceeding the EU's upper limit of 2.0 mg kg$^{-1}$. Potential sources of Cr contamination in pet food include the use of contaminated raw materials such as grains and meat by-products, contact with processing equipment, and exposure to polluted water or soils during cultivation or industrial contamination.[38] Co levels remained well within the AAFCO limit of 1.0 mg kg$^{-1}$, with a mean of 0.30 mg kg$^{-1}$.[39] Cu, with a wide variability (mean: 15.38 mg kg$^{-1}$, IQR: 3.55–28.69), stayed below both FDA (100 mg kg$^{-1}$) and EFSA (30 mg kg$^{-1}$) thresholds, though some samples neared the EFSA limit.[5,6] Zn had a high mean value of 165.84 mg kg$^{-1}$, exceeding EFSA's limit of 120 mg kg$^{-1}$ in several cases and approaching the FDA threshold of 250 mg kg$^{-1}$, indicating possible supplementation excess.[32] As concentrations, averaging 0.19 mg kg$^{-1}$, surpassed the EFSA limit of 0.1 mg kg$^{-1}$ but remained below AAFCO's 2.0 mg kg$^{-1}$, raising concerns due to its chronic toxicity.[33,39] Mo levels (mean: 0.82 mg kg$^{-1}$) were within safe boundaries under the AAFCO limit of 5.0 mg kg$^{-1}$. However, Cd presented a mean of 0.22 mg kg$^{-1}$—more than double the EU limit of 0.1 mg kg$^{-1}$—indicating a potential health hazard. Hg was particularly alarming, with a mean of 1.21 mg kg$^{-1}$ and an interquartile range of 1.14–1.37 mg kg$^{-1}$, which greatly exceeded both the FDA (0.1 mg kg$^{-1}$) and the stricter EFSA (0.01 mg kg$^{-1}$) limits, signifying a serious contamination issue.[5,6] Pb showed a mean of 0.65 mg kg$^{-1}$, under the FDA's upper limit of 10.0 mg kg$^{-1}$ but significantly above EFSA's limit of 0.1 mg kg$^{-1}$, suggesting a possible long-term exposure risk.[5,6] Overall, the data highlights critical exceedances, particularly for Hg, Cd, Cr, and As, underscoring the urgent need for improved regulation, monitoring, and quality control in pet food manufacturing. A similar study investigating toxic metal contamination in commercial pet foods and their ingredients in the Brazilian market revealed alarming levels of aluminum (Al), uranium (U), and vanadium (V), Hg and Pb exceeding the FDA's maximum tolerable limits.[23] Interestingly, dry foods contained higher levels than wet foods. Wheat bran had the highest levels among carbohydrate sources, while animal by-products generally contained higher toxicity than plant-based ingredients. Pork fat had higher arsenic, mercury, and antimony levels than fish oil and poultry fat. Another study found that several commercial pet foods in US markets contain high Hg concentrations, sometimes exceeding expected levels based on ingredient labels.[40] The study analyzed total Hg and methylmercury in pet food products and used genetic tools to identify ingredient sources. While total Hg exceeded suggested limits in several products, methylmercury remained within safe levels. A recent study restricted to cat food samples marketed in UAE revealed that while 70% met international safety standards for metal concentrations, several dry

Table 7 Summary of toxic metal levels in pet food with reference standards

| Metal | Mean (mg kg$^{-1}$) | SD | IQR (mg kg$^{-1}$) | Reference upper limit (mg kg$^{-1}$) |
|---|---|---|---|---|
| Cr | 2.75 | 0.92 | 2.13–3.39 | 2.0 (EU)[38] |
| Co | 0.30 | 0.49 | 0.08–0.32 | 1.0 (AAFCO)[39] |
| Cu | 15.38 | 13.76 | 3.55–28.69 | 100.0 (FDA);[5] 30.0 (EFSA)[6] |
| Zn | 165.84 | 164.40 | 27.00–343.64 | 250.0 (FDA);[5] 120.0 (EFSA)[6] |
| As | 0.19 | 0.32 | 0.03–0.26 | 2.0 (AAFCO);[39] 0.1 (EFSA)[6] |
| Mo | 0.82 | 0.57 | 0.34–1.12 | 5.0 (AAFCO)[39] |
| Cd | 0.22 | 0.22 | 0.11–0.16 | 0.1 (EU)[38] |
| Hg | 1.21 | 0.25 | 1.14–1.37 | 0.1 (FDA);[5] 0.01 (EFSA)[6] |
| Pb | 0.65 | 0.68 | 0.24–0.89 | 10.0 (FDA);[5] 0.1 (EFSA)[6] |

 

food samples exceeded permissible limits for metals like Al, Co, Cu, Fe, Mn, and Zn. Dry foods generally contained higher metal levels than wet foods, and meat-based products showed higher contamination than chicken or fish-based varieties.[27]

Our findings align with international studies that have reported the presence of toxic metals in commercial pet foods, with both similarities and regional variations in concentrations. For example, elevated levels of Pb and As detected in our samples are consistent with reports from the United States and Europe, where Pb levels occasionally exceeded safety thresholds and As contamination was linked to fish-based ingredients.[26,41] Zn and copper Cu concentrations were also found to be significantly higher in dry pet food globally, as documented in studies from Brazil and China, supporting our observation of moisture content influencing metal retention.[23,29] However, regional discrepancies in Cd and Hg levels suggest differences in raw material sourcing, manufacturing practices, and environmental contamination. These comparisons reinforce the need for geographically tailored surveillance strategies.

## Conclusion

Toxic metal contamination in pet food is a growing concern due to its potential health risks, as chronic exposure to elements like lead, arsenic, cadmium, and mercury has been linked to severe physiological and neurological disorders in companion animals. These metals can enter pet food through contaminated raw ingredients, industrial processing, packaging materials, and environmental pollution, with some products exceeding regulatory safety thresholds. Despite guidelines from agencies like the FDA and European Food Safety Authority (EFSA), enforcement remains inconsistent, and standardized testing methods are lacking. Our findings highlight significant variability in toxic metal concentrations across different pet food types and regions, underscoring the need for stricter regulatory oversight, improved quality control, and comprehensive monitoring of raw materials. However, our study did not assess metal speciation, which could be crucial for understanding bioavailability and toxicity. Due to limitations, the sample collection was only cross-sectional and may not capture seasonal or batch-to-batch variability, Our future studies will focus on longitudinal monitoring of metal contamination across production cycles, source tracing to identify contamination points within the supply chain, and incorporation of metal speciation and bioaccessibility assays.

To mitigate risks, manufacturers must enhance transparency in ingredient sourcing and adhere to more rigorous safety standards, while consumers should prioritize products with independent safety certifications. Ensuring pet food safety requires collaboration between manufacturers, regulatory agencies, and researchers to reduce contamination risks and safeguard animal health. Future studies should further explore the bioavailability of toxic metals in pet food and assess long-term exposure effects to establish more precise safety standards. Establishing standardized regulatory limits and continuous surveillance programs will be essential for safeguarding pet health and ensuring product safety.

## Data availability

Data are provided within the manuscript or will be made available on request by the corresponding author.

## Author contributions

N. Alwan collected the samples. F. Haydous performed microwave digestion, ICP-MS measurements, and analyzed the data, A. Shehab performed microwave digestion, and analyzed the data, H. Hassan, N. Alwan and M. Serhan analyzed the data, H. Dimassi carried out the statistical analysis. E. Akoury designed the study, performed ICP-MS measurements, analyzed the data, and wrote the manuscript. All authors contributed to reviewing and editing the manuscript.

## Conflicts of interest

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

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