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Community cats managed under Trap–Neuter–Return as sentinels of human diet-linked chemical exposure across contrasting feeding contexts

María del Mar Travieso-Aja [a], Octavio P. Luzardo [a,b,*], Norberto Ruiz-Suárez [a], Manuel Zumbado [a,b], Ana Macías-Montes [a], Beatriz Martín-Cruz [a], Luis Alberto Henríquez-Hernández [a,b], Andrea Acosta-Dacal [a]

[a] Research Institute of Biomedical and Health Sciences (IUIBS), Universidad de Las Palmas de Gran Canaria, Paseo Blas Cabrera s/n, 35016, Las Palmas de Gran Canaria, Spain

[b] Spanish Biomedical Research Center in Physiopathology of Obesity and Nutrition (CIBERObn), Avda. Monforte de Lemos 5, Fuencarral-El Pardo, Madrid, 28029, Spain

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ABSTRACT

At the local scale, environmental surveillance often overlooks diet-related exposures. In this study, we examined whether community cats managed through Trap–Neuter–Return (TNR) programs could serve as effective sentinels of human-relevant chemical mixtures shaped by local food environments. Intraoperative whole blood samples from 205 free-roaming cats were collected on two islands of the Canary archipelago, La Graciosa (n = 107) and Gran Canaria (n = 98), and analyzed for 55 elements and >360 organic contaminants using validated ICP-MS and micro-QuEChERS LC/GC-MS/MS workflows. The islands displayed distinct chemical profiles. La Graciosa exhibited a coherent “marine/leftovers” signature, with elevated Hg, As, Se, and Sr, and higher composite burdens of persistent organics (ΣPOPs) and polycyclic aromatics hydrocarbons (ΣPAHs). In contrast, Gran Canaria showed higher concentrations of rare-earth and technology-related elements (ΣREEs), and other urban/industrial tracers, whereas Pb and Cd remained low in both cohorts. Although compound-level detections were limited for many organic contaminants, the summed metrics clearly differentiated the two islands and minimized zero-inflation. Fipronil and its metabolite fipronil-sulfide were detected at both sites, consistent with ectoparasiticide use during handling. Second-generation anticoagulant rodenticides were identified exclusively in Gran Canaria, consistent with their routine application in urban pest control. Integrating minimally invasive sampling within routine TNR programs yielded standardized chemical profiles without additional captures, providing a concise indicator panel (Hg, As, Se, Sr, ΣPOPs, ΣPAHs, and ΣREEs) suitable for cross-site screening. Overall, TNR-managed community cats provide practical sentinel signals of diet-linked chemical exposures at the local scale. Because cross-species toxicokinetic differences preclude direct quantitative translation to humans, these results are interpreted as sentinel signals to prioritize follow-up rather than as evidence of human risk. The strength and internal consistency of the La Graciosa signal support targeted human biomonitoring on the island, prioritizing methylmercury and arsenic speciation together with focused dietary and source-apportionment surveys. Broader adoption of this TNR-based framework could enable One Health chemical surveillance across municipalities and seasons.

1. Introduction

Environmental pollution is a major driver of ecological degradation and human exposure, as complex mixtures of chemicals enter air, water, soils, and food webs (Escher et al., 2020; Pourchet et al., 2020). Metals and metalloids, persistent organic pollutants (POPs), and semi-persistent hydrocarbons can bioaccumulate and biomagnify along trophic chains, as shown by recent studies on food-web and seafood contamination (Lee et al., 2023; Primost et al., 2024). Yet many monitoring programs still emphasize abiotic matrices or wildlife that is hard to sample repeatedly, limiting temporal and spatial resolution (Dulsat-Masvidal et al., 2021; Espín et al., 2016). This leaves a gap in

* Corresponding author. Toxicology Unit, Clinical Sciences Department, Universidad de Las Palmas de Gran Canaria, Paseo Blas Cabrera Felipe s/n, 35016, Las Palmas, Spain.

E-mail address: octavio.perez@ulpgc.es (O.P. Luzardo).

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routine surveillance of diet-related human exposure and calls for diet-informed, One Health approaches—here referring to an integrated human–animal–environment health framework to support surveillance across shared exposure pathways—that are scalable, ethically acceptable, and deliver decision-relevant data within exposome-oriented frameworks. Such approaches should rely on harmonized analytical methods and, where feasible, non-invasive biomonitoring strategies (Alves et al., 2014; Matus et al., 2024; Pourchet et al., 2020).

Sentinel species provide a scalable strategy by integrating exposures over biologically meaningful time windows and offering early warnings for risk assessment and policy (Bertero et al., 2020; Hegedus et al., 2023; Schmidt, 2009). Classical sentinels—raptors, marine mammals, and freshwater fish—have yielded key insights but often face logistical and ethical constraints (rarity, protection, specialized capture) that limit sampling frequency and spatial coverage (Dulsat-Masvidal et al., 2021). Domestic and peri-domestic species offer a pragmatic alternative because they share space and exposure pathways with humans and are predictably accessible (Backer et al., 2001; Bertero et al., 2020; Hegedus et al., 2023; Schmidt, 2009). While aquatic sentinels (e.g., fish and marine mammals) are highly informative for marine food-web contamination, they are less suited to capturing neighborhood-scale, human-subsidized feeding contexts and are often constrained by protection status and sampling logistics. In contrast, community cats and other domestic/peridomestic species share human space and food environments and can therefore provide practical, diet-informed sentinel signals relevant to local human exposure pathways. Among these, free-roaming domestic cats (*Felis catus*) maintained in managed colonies are particularly promising because they show strong site fidelity and relatively small home ranges (Jensen et al., 2022; Lázaro et al., 2024; Philippe-Lesaffre et al., 2024). Dogs have also been used as sentinels, but cats' obligate carnivory and pollutant-class–specific bioaccumulation patterns can make them particularly responsive to diet-mediated signals in human-proximate food environments. Their routine handling in Trap-Neuter-Return (TNR) programs can be leveraged to obtain biospecimens at scale, providing neighborhood-level proxies of human diet-linked chemical exposure.

In Spain, recent national animal-welfare regulations mandate systematic sterilization and management of community-cat colonies via municipal programs (BOE, 2023; Spanish Directorate of Animal Rights, 2024). The routine clinical procedures in TNR create a One Health opportunity to integrate biomonitoring into existing workflows, enabling standardized sampling at scale without extra captures (Baptista et al., 2024). Colony-managed cats, provisioned by caretakers yet accessing human-derived foods, can reflect diet-mediated exposure pathways relevant to environmental and public-health surveillance (Piontek et al., 2021; Spanish Directorate of Animal Rights, 2024). Experimental work shows that food distribution shapes social interactions and aggregation around anthropogenic resources, facilitating predictable sampling (Solomon et al., 2025). At capture for sterilization, many cats depend on human food (caretaker leftovers and scavenging of domestic/restaurant waste), whereas post-TNR colonies typically shift to controlled provisioning, mainly commercial kibble, under municipal guidelines. Sampling at trapping thus captures a human-relevant, pre-standardization window informative for diet-linked exposure mixtures, although not universally. Given Spain's extensive network of managed colonies (approximately 1.8 million cats across more than 125,000 colonies), leveraging TNR touchpoints could provide a scalable sentinel framework for chemical biomonitoring (Luzardo et al., 2025b).

Islands provide ideal testbeds because clear boundaries aid source attribution and archipelagos offer socio-ecological contrasts that generate informative exposure gradients (Medina and Nogales, 2009). Within the Canary Islands, La Graciosa—a small, protected island with low resident population—differs markedly from more densely populated, industrially influenced areas of Gran Canaria (Luzardo et al., 2025a). These settings also diverge in food environments (supply chains, tourism intensity, household/restaurant waste) and in colony-management practices such as routine caretaker provisioning (Spanish Directorate of Animal Rights, 2024). Such differences likely affect both magnitude and composition of anthropogenic, diet-related inputs available to colony cats, consistent with evidence that urban provisioning shapes feline diets and that food availability structures aggregation and predictability within colonies (Piontek et al., 2021; Solomon et al., 2025). Here, we compare La Graciosa and Gran Canaria to test whether blood contaminant profiles in colony-managed cats reflect diet-related anthropogenic exposure pathways across contrasting island contexts.

Against this backdrop, we assessed contaminants in blood from colony-managed cats captured during TNR on La Graciosa and Gran Canaria, quantifying fifty-five elements—including essential, macro, and toxic elements—and more than 360 organic compounds (pesticides, veterinary drugs, human pharmaceuticals, POPs, and PAHs) using high-throughput analytical chemistry (Acosta-Dacal et al., 2025; González-Antuña et al., 2017; Rial-Berriel et al., 2020b). The study pursued three objectives: (i) characterize the occurrence and variability of blood concentrations across this broad suite of inorganic and organic contaminants in cats from both islands; (ii) test whether between-island differences are consistent with diet-linked anthropogenic exposure pathways—particularly contributions from human leftovers and waste streams typical of the pre-sterilization phase—while recognizing that other concurrent pathways (e.g., air/dust/soil and drinking water) may also contribute and cannot disentangled in this observational design; and (iii) evaluate the operational feasibility and standardization potential of embedding biospecimen collection for chemical biomonitoring within TNR clinical workflows across managed colonies, as a platform to prioritize and inform future multi-matrix and/or human biomonitoring follow-up.

2. Material and methods

2.1. Study context and sites

La Graciosa, part of the Chinijo Archipelago (Canary Islands, Spain), is a small arid island (29 km^2; ~800 residents; ~350,000 visitors in 2024) within a Natura 2000 complex. Human settlement is concentrated in Caleta de Sebo and Pedro Barba. Intense, ferry-linked tourism over limited infrastructure creates strong human–environment interfaces and multiple anthropogenic food sources (unsecured refuse, restaurant waste, direct feeding), around which free-roaming cats aggregate. Previous work shows colonies cluster near settlements, rely heavily on human-subsidized resources, and operate within administrative and conservation constraints (Luzardo et al., 2025a). This combination of clear boundaries, concentrated activity, and predictable access makes La Graciosa an informative model for assessing diet-linked exposure pathways in colony-managed cats.

Gran Canaria (1560 km^2; ~875,000 residents; ~4.72 million visitors in 2024) offers a contrasting, more urbanized and socioeconomically diverse setting within the same archipelago. Dense urban areas and tourism corridors generate abundant hospitality waste, while peri-urban/rural zones host routinely provisioned colonies. Provincial PACF materials compiled for the Canary Islands reflect rapid expansion in colony registration as Law July 2023 is implemented, with municipal program reports indicating ongoing, large-scale management (Luzardo et al., 2025b). Collectively, these features position Gran Canaria as a complementary, high-intensity anthropogenic food environment relative to La Graciosa, enabling a two-island comparison of diet-related inputs relevant to human exposure proxies.

2.2. Animals, sampling, and ethics

We included 205 community cats: 107 from La Graciosa and 98 from Gran Canaria (two additional La Graciosa samples were collected but excluded after QC). All were free-roaming colony members processed within municipal TNR programs. Inclusion required clinical suitability for routine sterilization and no anesthesia contraindications. Cats were captured and handled under standard TNR procedures with caretaker/municipal coordination and returned to their colonies after recovery.

Baseline descriptors were recorded during routine TNR clinical assessment. In La Graciosa, body condition score (BCS) was predominantly moderate-to-good (BCS 5 in 78/107, BCS 4 in 24/107, BCS 6 in 2/107, and BCS 3 in 3/107); sampled cats were predominantly adults and sex distribution was approximately balanced. In Gran Canaria, all sampled cats were older than 6 months, sex ratio was approximately balanced, and body condition was typically within BCS 4–5.

Whole blood was collected intraoperatively by licensed veterinarians under general anesthesia, using contaminant-free materials. Aliquots were uniquely labeled (colony/location georeferencing), immediately cooled, transported on dry ice, and stored frozen under chain-of-custody. This workflow embeds biospecimen collection into clinical practice and minimizes additional handling (Luzardo et al., 2025a).

Feeding context differed between islands. La Graciosa colonies at capture relied less on commercial kibble; tourism generates plentiful leftovers, some caretakers do not routinely provide kibble, and a subset of free-roaming cats forage around refuse and restaurant areas outside strict colony definitions. Post-TNR, municipal guidelines typically shift provisioning toward controlled kibble (Municipality of Teguise). In Gran Canaria, sampled colonies were under controlled caretaker provisioning predominantly with commercial kibble at sampling.

Because diet was not experimentally controlled or recorded individually, blood chemistry is interpreted as an integrator of recent in situ diet. Provisioning context was recorded at colony/local-aggregation level; island contrasts are framed as consistent with diet-linked anthropogenic inputs rather than evidence of specific food items. Food items were not quantified nor chemically analyzed; the ‘food environment’ descriptor reflects field provisioning context only. We also recognize that concurrent exposure from environmental media (e.g., airborne particles, soil/dust ingestion via grooming, and drinking water) may contribute to blood burdens and cannot be ruled out in this observational design.

All procedures complied with Spanish animal-welfare regulations and municipal TNR frameworks. Sampling occurred exclusively during routine sterilization, with no interventions beyond standard veterinary practice. Ethical approval was granted by the Ethics Committee for Animal Experimentation, University of Las Palmas de Gran Canaria (Resolution OEBA_ULPGC_35/2023).

2.3. Inorganic analytes and analytical methods

The inorganic panel included 55 elements of nutritional, toxicological, and environmental relevance. Macroelements: sodium (Na), magnesium (Mg), phosphorus (P), sulfur (S), potassium (K), calcium (Ca). Essential trace elements: lithium (Li), manganese (Mn), iron (Fe), cobalt (Co), zinc (Zn), copper (Cu), selenium (Se), molybdenum (Mo). Toxic heavy metals: arsenic (As), cadmium (Cd), mercury (Hg), lead (Pb). Additional environmentally relevant elements: beryllium (Be), boron (B), titanium (Ti), vanadium (V), chromium (Cr), nickel (Ni), strontium (Sr), tin (Sn), antimony (Sb), cesium (Cs), barium (Ba), bismuth (Bi), thallium (Tl), thorium (Th), uranium (U). Rare earths and technology-critical elements: gallium (Ga), yttrium (Y), niobium (Nb), ruthenium (Ru), indium (In), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), tantalum (Ta), platinum (Pt), and gold (Au).

Whole blood was digested by microwave-assisted acid digestion. Duplicate 250 mg aliquots were placed in PTFE vessels with 3.5 mL ultrapure water and 1.25 mL sub-boiled HNO_3 (65%) and run on a four-step program (5 min 100 °C; 5 min 150 °C; 8 min 200 °C; 7 min 200 °C). After cooling, digests were brought to 7.5 mL with ultrapure water. An internal-standard mix (Sc, Ge, Rh, Ir; 20 μg/mL in the spike) was added before analysis to correct drift/matrix effects, and procedural blanks accompanied each batch (Acosta-Dacal et al., 2025; González-Antuña et al., 2017).

Elements were quantified on an Agilent 7900 ICP-MS with MicroMist nebulizer, nickel cones, UHMI, and He collision cell (ORS4). Daily tuning used a multielement solution; data were acquired in discrete-sampling mode (ISIS) and processed with MassHunter v4.2.

Calibration used certified single-element stocks (100 mg/L, 5% HNO_3). Two 10-point external curves (main metals; REEs/technology-critical elements) covered 0.005–20 ng/mL with linearity $R^2 > 0.998$.

Performance followed published validation: mean recoveries 87–128%; precision from replicate spikes at 0.05/0.5/5 ng/mL with RSDs generally <8% (15–16% at the lowest level for some elements, e.g., Cu, Ni, Se, Sm, Fe, Ba, Zn). Operational LOQs were estimated from procedural blanks (n = 20) as 3 × SD; treatment of <LOQ values is detailed in Section 2.5.

2.4. Organic analytes and analytical methods

To complement elemental exposure, we applied a broad multiresidue workflow in whole blood: a miniaturized micro-QuEChERS extraction coupled to dual LC–MS/MS and GC–MS/MS determination (Rial-Berriel et al., 2020b). The target list comprised 360 compounds spanning pesticides (organochlorine, organophosphorus, carbamates, pyrethroids, fungicides, herbicides), POPs (PCBs, OCPs), PAHs, BDEs, anticoagulant rodenticides, veterinary/human pharmaceuticals, and selected metabolites/by-products. The method requires 250 μL per sample and achieves sub-ppb quantification across classes, as previously validated for wildlife biomonitoring (Rial-Berriel et al., 2020b).

Whole-blood aliquots were thawed, gently homogenized, and 250 μL transferred to 2 mL tubes. A 10 μL procedural internal-standard (P-IS) mix (final 1 ng mL^{-1} per P-IS) was added to samples, blanks, and calibrators, followed by vortexing and 1 h orbital shaking. Proteins were precipitated with 500 μL acetonitrile/1% formic acid; after vortexing and 20 min sonication, salts ($MgSO_4$ 150 mg; sodium acetate 37.5 mg) were added, vortexed, shaken 1 min, and micro-centrifuged (4200 rpm, 5 min). The supernatant (400 μL) was filtered (0.2 μm PET) into amber-insert vials and injected into both systems without further cleanup.

Instrumentation comprised UHPLC (Agilent 1290 Infinity II)–triple quadrupole (Agilent 6460, Jet Stream ESI) in dynamic MRM with polarity switching, using an EC-C18 (2.1 × 100 mm, 2.7 μm) column and a water (2 mM ammonium acetate, 0.1% formic acid)/methanol (2 mM ammonium acetate) gradient; flow 0.4 mL min^{-1}, 8 μL injections, 50 °C. GC–MS/MS used an Agilent 7890B–7010 (EI), pulsed splitless 1.5 μL injections onto twin HP-5MS columns with backflush; a fast oven ramp ensured coverage of the multiclass panel with timed MRM across 24 segments.

Quantification used matrix-matched calibration (12 points, 0.1–20 ng mL^{-1}) prepared fresh for each run and processed like samples. QC included procedural blanks and fortified matrix controls (0.2, 2, 10 ng mL^{-1}; ≥1/20 samples). Identification required ≥2 MRM transitions, retention-time match ±0.1 min, and ion-ratio agreement ±30% versus calibrators; off-scale samples were re-injected after dilution. Acceptance and validation criteria followed EU SANTE/12682/2019 (adapted to biological matrices) (EC, 2019; European Commission, 2019).

Performance matched prior validation: linearity R^2 0.97–0.99; recoveries typically 70–120% with intra/inter-day RSDs <20%. LOQs were the lowest calibrators meeting identity, bias, and precision; ~95% of analytes had LOQs <1.5 ng mL^{-1}. Matrix effects were controlled via matrix-matched calibration and internal standards; carryover was checked with post-high-standard blanks.

Concentrations are reported as ng mL^{-1} whole blood; μg kg^{-1} can be approximated assuming 1 kg L^{-1} for legacy comparisons. Full analyte lists, transitions, collision energies, retention windows, and detailed validation and applications are published elsewhere (Rial-Berriel et al., 2020b, 2020a).

2.5. Statistical analysis

We summarized continuous variables as medians and interquartile ranges (P25–P75), and categorical variables as counts and percentages. Normality was screened (Kolmogorov–Smirnov). Owing to non-normality and censoring, between-island comparisons used non-parametric tests: Mann–Whitney U (two-sided) as primary and Kruskal–Wallis as robustness check; sex and other categorical variables used chi-square or Fisher's exact tests. Statistical significance was set at $p \leq 0.05$.

Left-censored data were treated as follows: values < LOD were considered undetected (excluded from rank-based tests but included in detection frequencies); values LOD–LOQ were imputed by drawing a random value from a uniform distribution within that interval. The same approach preceded composite metrics and any transformations.

Rare earth and technology-critical elements were additionally summarized as ΣREEs (sum of individual concentrations, ng mL^{-1}). Non-parametric tests and summaries were run in GraphPad Prism v9.3. Additionally, pairwise Spearman correlation matrices were computed and visualized as heatmaps for inorganic elements and organic contaminants (Supplementary Fig. S1). For organic contaminants, zeros (non-detects) were treated as missing values to mitigate bias due to zero inflation. All tests were two-sided and statistical significance was set at $\alpha = 0.05$.

3. Results

3.1. Inorganic elements

3.1.1. Essential and macroelements

Across essential elements measured in whole blood (μg/L; Table 1 upper panel), clear between-island differences emerged. Unless otherwise stated, all p-values reported in the Results derive from two-sided Mann–Whitney U tests comparing islands.La Graciosa showed higher median concentrations for manganese and zinc (Mn 26.3 vs 0.0; Zn 5379.3 vs 2735.7; ~2.0-fold; both $p < 0.001$), as well as selenium (529.4 vs 452.2; ~1.17-fold; $p < 0.001$). In contrast, cobalt was elevated in Gran Canaria (1.0 vs 0.5; ~2.0-fold; $p < 0.001$). Copper displayed similar central tendencies between islands (933–942 ng/mL; $p = 0.287$), and iron, reflecting total hemoglobin-bound iron in whole blood, also showed no significant difference (3.00×10^5 vs 3.10×10^5 ng/mL; $p = 0.094$). Lithium showed very low median values on both islands, with a slight rightward shift in La Graciosa ($p < 0.001$). Molybdenum frequently fell at or below reporting limits in both groups (medians 0.0), although the distribution tails produced a small but statistically significant island effect ($p = 0.002$).

For macroelements (μg/mL; Table 1 lower panel), sodium and potassium concentrations were higher in Gran Canaria (Na 8482.9 vs 4820.5; ~1.76-fold; K 4800.4 vs 1394.6; ~3.44-fold; both $p < 0.001$), while magnesium and phosphorus were higher in La Graciosa (Mg 30.4 vs 17.364; ~1.75-fold; P 215.2 vs 180.3; ~1.19-fold; both $p < 0.001$). Calcium was slightly higher in La Graciosa (47.1 vs 40.3; $p = 0.004$), and sulfur showed a minor but significant difference (1557.3 vs 1502.7; $p = 0.020$). These contrasts were consistent across medians and interquartile ranges and were confirmed by non-parametric testing (U-Mann Whitney tests). These contrasts are evident in Table 1 and are summarized here to highlight the magnitude of the main between-island shifts.

3.1.2. Toxic and potentially toxic elements

Marked between-island contrasts were also observed for toxic and potentially toxic metals. For highly toxic elements, La Graciosa showed substantially higher whole-blood medians for mercury and arsenic compared with Gran Canaria (Hg 209.5 vs 32.0 μg/L; ~6.5-fold; As 94.3 vs 32.2 μg/L; ~2.9-fold; both $p < 0.001$). Lead showed the opposite trend, with higher median values in Gran Canaria (8.0 vs 3.6 μg/L; ~2.2-fold; $p < 0.001$), although its distribution was right-skewed due to several elevated values. Cadmium was largely undetectable on both islands, with medians at 0.0 μg/L (Table 2).

For potentially toxic and technology-related elements (Table 3), La Graciosa exhibited higher strontium and nickel (Sr 95.6 vs 33.6 μg/L; ~2.8-fold; Ni 29.9 vs 0.0 μg/L; both $p < 0.001$), whereas Gran Canaria showed higher levels of rubidium, antimony, tin, and gallium (Rb 323.7 vs 250.8 μg/L; ~1.3-fold; Sb 35.6 vs 8.2 μg/L; ~4.3-fold; Sn 1.5 vs 0.0 μg/L; Ga 4.8 vs 0.8 μg/L; ~6.0-fold; all $p < 0.001$). Aluminum displayed a contrasting dispersion pattern, with a higher median tendency in La Graciosa (326.4 vs 0.0 μg/L; $p < 0.001$) but a pronounced right tail in Gran Canaria. Vanadium was ~4.0-fold higher in La Graciosa (2.9 vs 0.7 μg/L; $p < 0.001$). The rare-earth element family, summarized as a composite variable, was higher in Gran Canaria (ΣREE median 0.7 vs 0.3 μg/L; ~2.3-fold; $p < 0.001$), consistent with the principal components analysis, which grouped REEs and technology-critical elements along a common axis.

3.2. Organic contaminants

Organic contaminants in whole blood showed generally low

Table 1
Essential and macroelements in community cats from Gran Canaria and La Graciosa.

Essential Element [a]	GRAN CANARIA		LA GRACIOSA		p-Value
	Mean ± SD	Median [P25–P75]	Mean ± SD	Median [P25–P75]	
Li	1.1 ± 4.1	0.0 [0.0–0.0]	6.12 ± 10.1	0.0 [0.0–9.2]	<0.001
Mn	14.2 ± 29.9	0.0 [0.0–25.7]	27.8 ± 11.7	26.3 [21.0–35.4]	<0.001
Fe	304,056.2 ± 81968.0	299,591.1 [262,134.2–330,721.2]	315,283.0 ± 61,310.6	309,881.0 [278,669.0–343,050.4]	0.094
Co	3.2 ± 8.4	1.0 [0.6–2.2]	0.8 ± 1.0	0.5 [0.0–1.1]	<0.001
Zn	3060.6 ± 2649.2	2735.7 [2369.9–3149.7]	6230.1 ± 3456.2	5379.3 [3926.1–7141.5]	<0.001
Cu	918.6 ± 416.7	933.1 [764.4–1124.6]	1019.1 ± 316.7	942.4 [814.2–1139.0]	0.287
Se	432.5 ± 135.6	452.2 [360.6–519.2]	514.2 ± 113.5	529.4 [432.4–588.8]	<0.001
Mo	5.6 ± 16.0	0.0 [0.0–2.7]	6.2 ± 24.0	0.0 [0.0–0.0]	0.002
Macroelement [a]	**Mean ± SD**	**Median [P25–P75]**	**Mean ± SD**	**Median [P25–P75]**	**p-Value**
Na	9125.7 ± 2473.1	8482.9 [7383.7–10,060.2]	4982.3 ± 1152.6	4820.5 [4388.7–5196.3]	<0.001
Mg	16.9 ± 7.9	17.4 [11.6–21.7]	29.7 ± 7.7	30.4 [24.6–34.3]	<0.001
P	176.4 ± 33.6	180.3 [159.0–193.8]	219.4 ± 31.2	215.2 [198.6–236.2]	<0.001
S	1493.7 ± 267.8	1502.7 [1408.4–1586.5]	1562.2 ± 168.3	1557.3 [1459.0–1669.9]	0.020
K	5583.9 ± 2373.3	4800.4 [4122.1–6437.3]	1509.0 ± 874.4	1394.6 [929.1–1685.6]	<0.001
Ca	39.9 ± 27.1	40.3 [29.8–48.5]	52.5 ± 30.9	47.1 [28.2–70.9]	0.004

Values are presented as mean ± SD and median [P25–P75]. P-values are from Mann–Whitney U tests comparing islands.
[a] Units: essential elements expressed as μg/L (equivalent to ng/mL); macroelements (Na, Mg, P, S, K, Ca) expressed as μg/mL (i.e., mg/L).

Table 2
Very toxic elements (As, Cd, Hg, Pb) in community cats from Gran Canaria and La Graciosa.

Element	GRAN CANARIA		LA GRACIOSA		
	Mean ± SD	Median [P25–P75]	Mean ± SD	Median [P25–P75]	*p*-value
As	38.6 ± 31.0	32.2 [20.4–48.9]	106.9 ± 60.1	94.3 [62.1–126.3]	<0.001
Cd	0.1 ± 0.3	0.0 [0.0–0.0]	0.0 ± 0.0	0.0 [0.0–0.0]	<0.001
Hg	43.6 ± 61.4	32.0 [20.3–51.1]	296.2 ± 286.2	209.5 [129.7–350.2]	<0.001
Pb	92.3 ± 646.7	8.0 [5.2–16.7]	9.1 ± 30.4	3.6 [0.0–7.7]	<0.001

Values are presented as mean ± SD and median [P25–P75]. P-values are from Mann–Whitney U tests comparing islands. Units are expressed as μg/L (equivalent to ng/mL).

Table 3
Potentially toxic elements in community cats from Gran Canaria and La Graciosa.

Element	GRAN CANARIA		LA GRACIOSA		
	Mean ± SD	Median [P25–P75]	Mean ± SD	Median [P25–P75]	*p*-Value
Al	361.9 ± 1725.6	0.0 [0.0–0.0]	507.7 ± 520.8	326.4 [159.5–689.8]	<0.001
Au	0.1 ± 0.5	0.0 [0.0–0.0]	0.1 ± 0.5	0.0 [0.0–0.0]	0.067
Ba	224.9 ± 1332.9	16.3 [10.2–35.5]	17.5 ± 129.3	0.0 [0.0–2.3]	<0.001
Be	0.2 ± 0.5	0.0 [0.0–0.0]	0.3 ± 1.1	0.0 [0.0–0.0]	0.872
Bi	0.0 ± 0.2	0.0 [0.0–0.0]	0.0 ± 0.0	0.0 [0.0–0.0]	0.019
Cr	39.5 ± 271.3	0.0 [0.0–0.0]	3.8 ± 11.0	0.0 [0.0–0.0]	0.603
Cs	3.2 ± 9.7	0.6 [0.0–2.8]	0.9 ± 1.2	0.2 [0.0–1.8]	0.081
Ga	101.1 ± 623.6	4.8 [0.0–10.2]	6.1 ± 37.3	0.8 [0.0–2.6]	<0.001
Ni	30.7 ± 97.6	0.0 [0.0–20.6]	33.6 ± 24.1	29.9 [21.3–38.0]	<0.001
Os	0.1 ± 0.2	0.0 [0.0–0.0]	0.0 ± 0.1	0.0 [0.0–0.0]	0.919
Pt	0.1 ± 0.4	0.0 [0.0–0.0]	0.1 ± 0.2	0.0 [0.0–0.0]	0.708
Rb	332.0 ± 113.8	323.7 [266.2–360.6]	268.9 ± 66.2	250.8 [221.1–305.8]	<0.001
Sb	42.8 ± 26.8	35.6 [31.3–45.0]	9.3 ± 7.0	8.2 [4.9–11.2]	<0.001
Sn	3.2 ± 5.0	1.5 [0.0–4.4]	0.8 ± 2.1	0.0 [0.0–0.2]	<0.001
Sr	28.1 ± 25.4	33.6 [0.0–49.2]	114.4 ± 77.6	95.6 [56.9–149.6]	<0.001
Th	0.0 ± 0.1	0.0 [0.0–0.0]	0.0 ± 0.1	0.0 [0.0–0.0]	1.000
Ti	35.1 ± 163.5	0.0 [0.0–13.7]	9.0 ± 8.6	7.8 [4.5–11.7]	0.029
U	0.0 ± 0.1	0.0 [0.0–0.0]	0.0 ± 0.0	0.0 [0.0–0.0]	<0.001
V	2.4 ± 12.6	0.7 [0.0–1.5]	4.2 ± 4.1	2.9 [0.9–6.1]	<0.001
Sum REE	3.5 ± 8.0	0.7 [0.3–1.7]	0.7 ± 1.1	0.3 [0.2–0.7]	<0.001

Values are presented as mean ± SD and median [P25–P75]. P-values are from Mann–Whitney U tests comparing islands. Units are expressed as μg/L (equivalent to ng/mL).

detection frequencies at the individual compound level (here defined as <25% of samples above the reporting limit), but a clear island-level separation when considered as totals. The sum metrics for persistent organic pollutants (POPs) and for polycyclic aromatic hydrocarbons (PAHs) were both higher in La Graciosa than in Gran Canaria, with non-parametric tests confirming significant differences ($p < 0.001$ in both cases). The shift in medians and interquartile ranges is evident in the boxplots and consistent with the compound-level detection data (Fig. 1). Correlation heatmaps (Supplementary Fig. S1) are provided as a descriptive visualization of co-variation patterns among detected inorganic and organic panels, supporting the island-level contrasts reported above.

Among non-persistent and veterinary-use compounds, fipronil and its sulfide metabolite were the most frequently detected analytes on both islands, with notably higher detections counts in La Graciosa. Fipronil was detected in 52 cats from La Graciosa and 18 from Gran Canaria, with median concentrations of 1.6 [1.0–3.2] ng/mL and 3.2 [1.3–6.3] ng/mL, respectively. Fipronil-sulfide was detected in 51 cats in La Graciosa and 27 in Gran Canaria, showing broadly comparable medians around 1.7–1.8 ng/mL. Several other non-persistent insecticides appeared

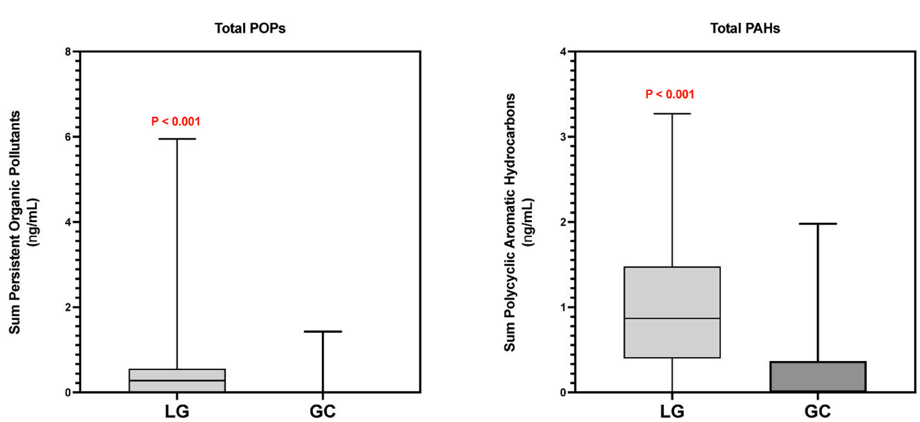

Fig. 1. Whole-blood composite burdens of persistent organic pollutants (ΣPOPs) and polycyclic aromatic hydrocarbons (ΣPAHs) in community cats from La Graciosa (LG, n = 107) and Gran Canaria (GC, n = 98). Boxplots display medians and interquartile ranges; whiskers show dispersion. Σ metrics are the per-sample sums of quantified compounds (ng/mL). Between-island differences were assessed with Mann–Whitney U tests (both $P < 0.001$).

sporadically and were island-specific: permethrin, eprinomectin, pyriproxyfen and second-generation anticoagulant rodenticides (brodifacoum, flocoumafen) were found only in Gran Canaria, while diflubenzuron and lufenuron were detected only in La Graciosa. Given the high proportion of non-detects, p-values were not computed (Table 4).

Within persistent and semi-persistent classes (i.e., legacy POPs—DDE/HCB/lindane and PCB congeners—and PAHs), detections were more frequent in La Graciosa (i.e., more compounds detected and more cats with detectable concentrations) than in Gran Canaria. DDE and multiple PCB congeners (138, 153, 180) were detected in a much greater number of cats from La Graciosa compared with Gran Canaria, despite similar or slightly lower medians at the compound level. HCB and lindane were only detected in La Graciosa, albeit at low counts. For PAHs, fluoranthene and pyrene were exclusively found in La Graciosa (n = 25 and n = 59, respectively). Fluorene occurred in both islands but was more frequent in La Graciosa (71 vs 21 detections; medians around 0.4–0.6 ng/mL), and naphthalene showed a higher median concentration in La Graciosa (1.0 vs 0.4 ng/mL). As with the non-persistent compounds, formal hypothesis testing was not conducted for these low-frequency detections (Table 4). Taken together, the sum metrics and compound-level data consistently indicate higher overall POP and PAH burdens in cats from La Graciosa at the time of sampling.

4. Discussion

The present findings reveal a coherent (i.e., directionally consistent across multiple markers and classes) diet-linked exposure signature in community cats sampled during TNR, with clear island separation spanning inorganic markers (notably Hg, As, Se, Sr), composite organic burdens (ΣPOPs, ΣPAHs) and technology-related elements (ΣREEs). These patterns mirror the contrasting feeding contexts at capture and illustrate how whole-blood biomonitoring in colony cats can operate as a practical sentinel of human-relevant exposure mixtures within routine TNR clinical workflows (trap–intake, brief clinical assessment, anesthesia/surgery, perioperative care, and release), where intraoperative blood sampling can be integrated without additional captures. We first consider essential and macroelements as a nutritional backdrop before interpreting toxic and semi-persistent signatures within a One Health frame (integrating human, animal, and environmental health).

4.1. Inorganic elements: nutritional insights and exposure contrasts

4.1.1. Essential and macroelements: nutritional assessment

Interpreting whole-blood essentials requires caution because most veterinary reference intervals are serum-based and not directly transferable. However, for elements with available whole-blood references or defensible extrapolations, both island cohorts appear broadly compatible with published feline or typical whole-blood concentrations, with no clear group-level signal of deficiency or excess. Whole-blood Cu medians around 933–942 ng/mL fall well within reported feline ranges, consistent with nutritional sufficiency (Fascetti et al., 2002). For Se, feline whole-blood and plasma concentrations are of similar magnitude and track intake; our medians (La Graciosa 529 ng/mL; Gran Canaria 452 ng/mL) also fall within published whole-blood levels (Todd et al., 2012). Whole-blood Zn typically exceeds serum because of erythrocyte partitioning and hematocrit effects; in this context, our medians (Gran Canaria 2736 ng/mL; La Graciosa 5380 ng/mL) remain compatible with nutritional sufficiency of Zn given interindividual variability (Buxaderas and Farré-Rovira, 1985; Sedláčková et al., 2022).

Lower-abundance essentials are more difficult to interpret. Human population data place whole-blood Mn in the single-digit ng/mL range; La Graciosa's median (26.3 ng/mL) appears elevated, whereas frequent non-detects in Gran Canaria suggest lower exposure or left-censoring, although interspecies differences and red-cell partitioning limit direct extrapolation to cats (Milne et al., 1990). For Mo, the absence of feline whole-blood reference intervals means that published human values can provide only qualitative context; widespread $\leq$ LOQ values on both islands are consistent with very low circulating Mo (Schultze et al., 2014). For Co, circulating totals mainly reflect cobalamin biology, so modest island contrasts should be interpreted conservatively (Kunath et al., 2024). Whole-blood Fe largely mirrors hemoglobin mass rather that iron status, and the similar medians observed here ($3.0–3.1 \times 10^5$ ng/mL) are therefore best read as comparable hemoglobin pools rather

Table 4
Organic contaminants in community cats from Gran Canaria and La Graciosa: persistent/semi-persistent (POPs, PAHs) and non-persistent compounds.

Compound	GRAN CANARIA			LA GRACIOSA		
	Mean ± SD	Median [P25–P75]	Detected (n)	Mean ± SD	Median [P25–P75]	Detected (n)
Persistent pollutants						
DDE (*p,p′*)	0.2 ± 0.2	0.2 [0.1–0.3]	6	0.2 ± 0.1	0.1 [0.1–0.2]	61
Hexachlorobenzene (HCB)	—	—	0	0.3 ± 0.0	0.3 [0.3–0.3]	2
Lindane (γ-HCH)	—	—	0	1.1 ± 0.2	1.1 [1.0–1.1]	8
PCB-138	0.2 ± 0.1	0.2 [0.2–0.2]	5	0.1 ± 0.1	0.1 [0.1–0.2]	38
PCB-153	0.3 ± 0.2	0.2 [0.1–0.4]	8	0.2 ± 0.3	0.1 [0.1–0.2]	60
PCB-167	—	—	0	0.2	0.2 [0.2–0.2]	1
PCB-180	0.2 ± 0.1	0.3 [0.2–0.3]	3	0.2 ± 0.3	0.1 [0.1–0.1]	52
Semipersistent pollutants						
Fluoranthene	—	—	0	0.6 ± 0.1	0.6 [0.5–0.6]	25
Fluorene	0.6 ± 0.2	0.6 [0.4–0.7]	21	0.5 ± 0.3	0.4 [0.3–0.5]	71
Naphthalene	0.5 ± 0.4	0.4 [0.2–0.8]	17	1.0 ± 0.3	1.0 [0.9–1.2]	7
Phenanthrene	0.3 ± 0.0	0.3 [0.3–0.3]	3	0.3 ± 0.1	0.3 [0.3–0.3]	4
Pyrene	—	—	0	0.7 ± 0.4	0.7 [0.4–0.9]	59
Non persistent pollutants						
Diflubenzuron	—	—	0	3.0 ± 2.1	3.0 [2.2–3.7]	2
Fipronil	5.8 ± 6.7	3.2 [1.3–6.3]	18	4.5 ± 8.1	1.6 [1.0–3.2]	52
Fipronil-sulfide	6.2 ± 8.8	1.8 [1.2–6.1]	27	5.1 ± 10.2	1.7 [1.1–3.6]	51
Lufenuron	—	—	0	0.4	0.4 [0.4–0.4]	1
Permethrin	7.7 ± 9.8	1.7 [1.4–13.3]	6	—	—	0
Pyriproxifen	0.3 ± 0.1	0.3 [0.2–0.3]	2	—	—	0
Eprinomectin	3.1 ± 2.1	1.9 [1.8–3.7]	3	—	—	0
Brodifacoum	0.9 ± 0.3	0.9 [0.8–0.9]	5	—	—	0
Flocoumafen	0.3	0.3 [0.3–0.3]	1	—	—	0

Values are mean ± SD and median [P25–P75]. Units: ng/mL (≡ μg/L). "Detected (n)" is the number of samples with concentrations > LOQ. "—" indicates all values < LOQ. P-values are not computed because many analytes show zero inflation and low detection frequency between-island contrasts are instead interpreted from detection patterns and composite metrics.

than deficiency or overload (Jensen et al., 2025).

Macroelements in whole blood also warrant further restraint because most feline intervals are plasma or serum-based, and analytical as weel as population-level factors can influence measured concentrations (Reynolds et al., 2010; Trenholme et al., 2022; van den Broek et al., 2018; Trenholme et al., 2022; van den Broek et al., 2018)Overall, the essential-element profile is compatible with nutritional sufficiency in both cohorts. Accordingly, higher Zn/Se/Mn in La Graciosa—together with broadly similar Cu and Fe—are best interpreted as contextual markers of the local feeding environment, rather than evidence of deficiency or overload, and they provide a baseline for interpreting the toxic and semi-persistent exposure signatures reported below.

4.1.2. Exposure to toxic, potentially toxic, and technology-related elements

Whole-blood benchmarks for cats are scarce, so human biomonitoring serves only as context rather than for back-calculation of intake or risk. In U.S. surveys, whole-blood Hg typically lies at sub-μg/L levels (medians ~0.7 μg/L; 95th percentiles ~4–5 μg/L) (Yao et al., 2021). Against that backdrop, our medians—32 μg/L in Gran Canaria and 210 μg/L in La Graciosa—are ~45 × and ~300 × higher, respectively. Because blood Hg in fish-eating populations is predominantly methylmercury bound to erythrocytes, whole blood is an appropriate marker of recent dietary exposure and supports between-group contrasts (Esposito et al., 2019; Yao et al., 2021). Commercial dry foods can also contribute Hg and As, a plausible input where access to fish leftovers is limited, particularly in Gran Canaria (Macías-Montes et al., 2021).

Arsenic shows a similar elevation. Human background whole-blood As is generally in the low single-digit μg/L, whereas our medians (32.2 μg/L Gran Canaria; 94.3 μg/L La Graciosa) were clearly higher. La Graciosa aligns closely with reported feline whole-blood As (~102 μg/L), whereas Gran Canaria is lower but still above human background, again suggesting diet-linked inputs; measurable As in Spanish dry cat diets reinforces this interpretation (Macías-Montes et al., 2021).

By contrast, Pb and Cd do not drive the observed pattern. Adult human whole-blood Pb is around 12 μg/L, and Cd around 0.3–0.4 μg/L; feline medians here—Pb 8.0 μg/L (Gran Canaria) and 3.6 μg/L (La Graciosa)—fell within or below those human backgrounds, and Cd was largely non-detectable (Buser et al., 2016). This supports and exposure profile in which Hg and As are the dominant discriminants, with Pb and Cd contributing little, if at all(Chen et al., 2019) (Macías-Montes et al., 2021).

Several potentially toxic elements vary with context. Sr and Ni were higher in La Graciosa, consistent with stronger marine influence and local geochemistry, whereas V was only modestly higher and may reflect mixed marine and anthropogenic inputs in coastal settings (Babaahmadifooladi et al., 2020; Kučera et al., 1992; Ru et al., 2024; Watt et al., 2018). Aluminum showed a higher central tendency in La Graciosa, but its dispersion suggests multiple local inputs and supports interpretation as an exposure-context indicator rather than a clinical marker of toxicity or disease in individual cats (Igbokwe et al., 2020; Tietz et al., 2019).

Conversely, Rb, Sb, Sn, and Ga were higher in Gran Canaria, consistent with a more urban/industrial mixture potentially linked to processed-food chains, packaging/plumbing alloys, electronics residues, and indoor dust, although these remain hypotheses for follow-up rather than demonstrated sources (Brouziotis et al., 2022; Pagano et al., 2015; Tansel, 2017). The elevation of ΣREEs and other technology-critical elements in Gran Canaria further suggests an urban signature, and total REEs provide a practical family-level indicator when individual concentrations are low and correlated (Brouziotis et al., 2022; Tansel, 2017). From a surveillance perspective, pairing REEs as urban/-technology tracers with Hg, As, and Sr as marine-associated markers offers a compact set for rapid screening and prioritization in One Health monitoring (Brouziotis et al., 2022).

4.2. Organic contaminants: POP and PAH burdens, pesticides and contextual drivers

The organic-contaminant profile shows a clear island contrast driven by legacy POPs, PAHs, and selected pesticides. Total POPs and PAHs were higher in La Graciosa, alongside broader detection of organochlorine pesticides and multiple PAH congeners. These patterns are consistent with greater access to seafood-derived leftovers and marine-influenced food sources at the time of capture. Marine foods from Iberian coasts and the northeast Atlantic are known to carry legacy and emerging pollutants, including organochlorines and PAHs, supporting the plausibility of a seafood-linked burden in cats with access to fish waste (Henríquez-Hernández et al., 2017; Rodil et al., 2019; Rodríguez-Hernández et al., 2016).

Beyond persistent and semi-persistent burdens, fipronil and its sulfide metabolite were frequently detected. During our campaigns, topical ectoparasiticides formed part of routine colony care and the perioperative protocol, though precise timing relative to venipuncture was not recorded for all animals. These detections are therefore best read as procedural/zoosanitary markers rather than environmental or dietary exposure; any island differences likely reflect implementation logistics rather than true exposure contrasts.

The rodenticide pattern offers policy context. Residues were detected only in Gran Canaria, consistent with routine urban pest control, whereas their absence in La Graciosa aligns with stricter Natura 2000 (the EU network of protected areas designated under the Birds and Habitats Directives) constraints, where activities with potential ecological impact—including biocide use—are subject to precautionary oversight and often restricted (Möckel, 2022). Non-detection in La Graciosa is thus consistent with compliance, while detections in Gran Canaria plausibly reflect practices outside those protections.

Broader PAH detection and higher total PAHs in La Graciosa likely reflect access to fish-based leftovers and food-handling or preparation contexts that introduce these compounds, reinforcing a marine-linked signature in whole blood. Together with the separation observed for total POPs, these results suggest that a concise set of composite organic markers (total POPs, total PAHs) provides strong comparative power across sites without exhaustive compound-by-compound testing. Iberian/Atlantic seafood monitoring similarly reports detectable legacy POPs and PAHs in edible biota, consistent with the direction of effects observed here (Bedi et al., 2024; Rodil et al., 2019).

Finally, our findings agree with comparative work in companion animals showing species-specific accumulation. Despite higher estimated dietary POP intakes in dogs, circulating OCPs and PCBs tend to be higher in cats, reflecting differences in bioaccumulation and metabolism (Ruiz-Suárez et al., 2015). This supports prioritizing cats—particularly community cats sampled at TNR touchpoints—as responsive sentinels for legacy POPs in mixed urban–coastal settings where seafood exposure remains relevant.

4.3. Community cats at TNR capture stage as sentinels of human-relevant exposure

The combined inorganic–organic whole-blood profile supports community cats captured during TNR as sentinels of human-relevant exposure mixtures. As summarized in Fig. 2, biomarkers linked with marine intake (mercury, arsenic, selenium, and strontium), together with composite burdens of persistent organics (total POPs), were consistently higher in La Graciosa than in Gran Canaria, with clear separation between medians and interquartile ranges. This pattern aligns with the element-by-element summaries (Tables 2 and 3), which show parallel shifts in additional marine-associated markers.

The coherence of these signals indicates that samples colleted at trapping capture a stable snapshot of the local food environment. Field observations at colony level indicated frequent availability of seafood-related food waste in La Graciosa, consistent with the marine-

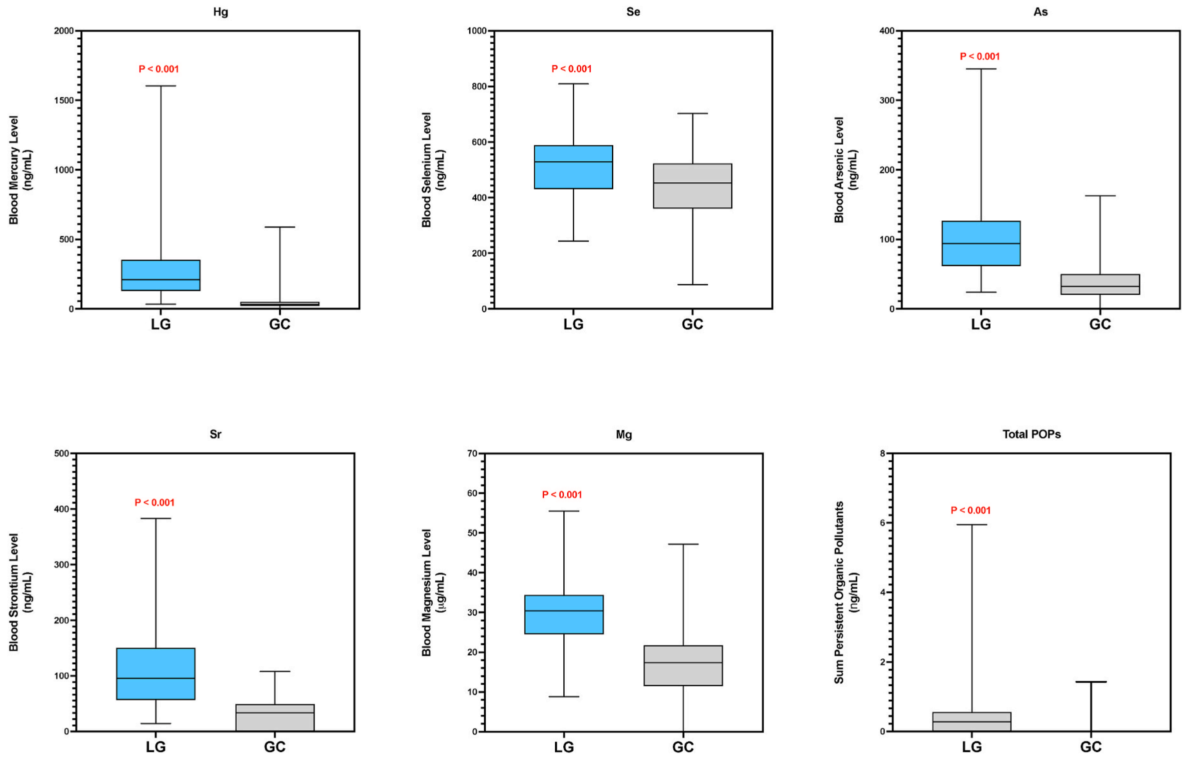

Fig. 2. Key whole-blood tracers in community cats from La Graciosa (LG, n = 107) and Gran Canaria (GC, n = 98): mercury (Hg), strontium (Sr), selenium (Se), magnesium (Mg; μg/mL), arsenic (As), and total persistent organic pollutants (ΣPOPs). Boxplots show medians and interquartile ranges; whiskers indicate dispersion. All between-island contrasts were significant (Mann–Whitney U, $P < 0.001$). Units: ng/mL unless otherwise indicated.

associated contaminant profile in cats. This pattern extends beyond inorganic tracers: PAHs are broader and higher in La Graciosa, with fluoranthene and pyrene frequently detected at median concentrations of 0.6 and 0.7 ng/mL, respectively, while both are undetected in Gran Canaria. Gran Canaria, in contrast, showed higher total REEs and several technology-related elements, pointing to a distinct, more urban and industrial exposure mixture. Food-processing evidence is also consistent with this interpretation, as grilled fish products typically contain substantially higher PAH loads than fried products, largely due to smoke deposition and fat dripping onto the heat source (Wang et al., 2021). Together, these features illustrate how colony cats integrate diet-derived and context-specific inputs, making them practical sentinels for environmental-health surveillance.

Several features enhance the translational value of this TNR-embedded sentinel-biomonitoring approach. Community cats share urban and peri-urban environments with humans, and their diets shift along the urbanization gradient, with greater reliance on anthropogenic foods in urban settings, strengthening their relevance as sentinels of local food environments (Piontek et al., 2021). Whole blood is an appropriate matrix because key diet-linked metals partition strongly into erythrocytes (Buchweitz et al., 2019; Chen et al., 2019; Mortensen et al., 2014), while composite organic metrics (total POPs, total PAHs) help to overcome the zero inflation that often limits single-compound analyses. The TNR workflow also enables standardized minimally invasive sampling during routine perioperative handling, without additional capture, improving feasibility and comparability across sites (Animais de Rua, 2024; ASPCA, 2016). Finally, summarizing REEs as a family metric helps distinguish urban-technology tracers from fish-associated elements in cross-site comparisons (Pagano et al., 2015; Tansel, 2017).

Elevated Hg–As–Se–Sr and total POPs/total PAHs in La Graciosa are consistent with frequent access to seafood-derived foods and waste, whereas the absence of anticoagulant rodenticide detections aligns with restrictions typical of protected Natura 2000 sites. Conversely, rodenticide residues detected only in Gran Canaria likely reflect routine urban pest-control practices rather than diet. Fipronil and fipronil-sulfide, although prominent in whole blood at both sites, mainly reflect peri-procedural ectoparasiticide use during sterilization and should be interpreted as procedural rather than environmental markers (Animais de Rua, 2024; ASPCA, 2016).

From a One Health perspective, the magnitude and internal consistency of the La Graciosa signature indicate that colony-cat biomonitoring can provide decision-relevant insights into neighborhood-level dietary exposures. Although toxicokinetic differences between cats and humans preclude direct quantitative translation, the combination of extreme whole-blood mercury and elevated total arsenic supports targeted human biomonitoring on the island, prioritizing methylmercury and arsenic speciation, together with concise dietary surveys and source-apportionment approaches. In parallel, the higher total REEs and technology-critical elements in Gran Canaria suggest that cats may also serve as sentinels of non-dietary anthropogenic inputs in more urbanized settings. Overall, the study provides a harmonized baseline characterization of a broad inorganic and organic contaminant panel in whole blood from TNR-managed community cats across two contrasting island settings, identifies structured between-island exposure patterns, and demonstrates the operational feasibility of embedding standardized biospecimen collection and chemical profiling within routine TNR workflows at scale.

4.4. *Limitations of the study*

Several uncertainties warrant caution. First, feline reference intervals are scarce and mostly serum-based, so nutritional interpretation of essentials required cross-matrix extrapolation (serum → whole blood) and, when feline ranges were unavailable, contextual use of human population values. Inter- and interspecies differences in erythrocyte partitioning—influenced by hematocrit and possible hemolysis—can shift absolute concentrations and complicate comparisons. Species-specific toxicokinetics further limit cross-species interpretation. Cats and humans may differ in gastrointestinal absorption, biotransformation capacity and elimination half-lives for several contaminant classes, so similar external exposures could yield different internal concentrations (and vice versa). Therefore, our study does not attempt to infer human internal dose or risk from feline blood levels; cats are used here as sentinels to compare exposure signatures across local contexts and to prioritize targeted human follow-up.

Second, arsenic speciation was not performed, likely overestimating the toxicologically relevant inorganic fraction. Methylmercury was not directly measured; its predominance in whole blood is inferred from prior literature rather than confirmed here. Third, LODs/LOQs introduced left-censoring for low-abundance analytes; although we used nonparametric tests and composite metrics, residual tail bias may persist.

In addition, individual-level clinical metadata were not fully harmonized across both campaigns (e.g., body weight, chronic disease and parasitism status), which may contribute to inter-individual variability in biomarker levels. Future field campaigns will standardize a minimal metadata set (e.g., weight, BCS and a brief health/parasitism checklist) to support covariate-adjusted analyses.

Finally, study design limits inference. Diet was not controlled individually, and feeding heterogeneity at capture—especially in colonies transitioning to standardized provisioning—may have amplified short-term meal signals; extrapolation to fully stabilized colonies should be cautious. Sampling was cross-sectional at a single perioperative time point, precluding temporal analyses (e.g., seasonality, within-individual change). Pet-food contamination context came from prior publications, not concurrent feed sampling, limiting direct source attribution. Moreover, we cannot exclude concurrent non-dietary pathways (air/dust/soil and drinking water), which may act as confounders and should be addressed in future multi-matrix follow-up. Future work could strengthen dietary source attribution by incorporating stable isotope ratios ($\delta^{13}C/\delta^{15}N$) and/or targeted multi-matrix sampling (food items, water, and dust/soil), which were beyond the scope of the present TNR-embedded design.

5. Conclusions

Community cats sampled under Trap–Neuter–Return provided a practical, minimally invasive window into diet-linked chemical exposure in human-proximate settings. Across contrasting feeding contexts, La Graciosa cats showed a clear marine-food chemical signature, with markedly higher whole-blood mercury and arsenic, and higher ΣPOPs/ΣPAHs than cats predominantly fed on kibble in Gran Canaria—patterns consistent with seafood-influenced inputs while recognizing that concurrent environmental-media exposures may also contribute. These findings position TNR programs as scalable platforms for ethical biomonitoring of anthropogenic, diet-mediated exposures, complementing conventional human surveys and enabling repeated, cost-effective assessments in island and other resource-limited contexts.

CRediT authorship contribution statement

María del Mar Travieso-Aja: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Formal analysis, Data curation, Conceptualization. **Octavio P. Luzardo:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Norberto Ruiz-Suárez:** Writing – review & editing, Investigation. **Manuel Zumbado:** Writing – review & editing, Methodology, Investigation. **Ana Macías-Montes:** Writing – review & editing, Investigation. **Beatriz Martín-Cruz:** Writing – review & editing, Investigation. **Luis Alberto Henríquez-Hernández:** Writing – review & editing, Investigation. **Andrea Acosta-Dacal:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2026.127964.

Data availability

Data will be made available on request.

References

Acosta-Dacal, A., Henríquez, A.M., Corbera, J.A., Macías-Montes, A., Zumbado, M., Ruiz-Suárez, N., Martín-Barrasa, J.L., Luzardo, O.P., Tejedor-Junco, M.T., 2025. Comprehensive profiling of essential elements and organic and inorganic contaminants in dromedary camels from the Canary Islands: a baseline for nutritional and environmental assessment. Vet. Sci. 12, 829. https://doi.org/10.3390/VETSCI12090829, 2025, Vol. 12, Page 829.

Alves, A., Kucharska, A., Erratico, C., Xu, F., Den Hond, E., Koppen, G., Vanermen, G., Covaci, A., Voorspoels, S., 2014. Human biomonitoring of emerging pollutants through non-invasive matrices: state of the art and future potential. Anal. Bioanal. Chem. https://doi.org/10.1007/s00216-014-7748-1.

Animais de Rua, 2024. Trap-neuter-return (TNR). Manual [WWW Document]. Animais de Rua, Lisbon, Portugal. URL. https://www.eurogroupforanimals.org/files/eurogroupforanimals/2023-08/2023-08-08-Animais%20de%20Rua%20-%20TNR%20Manual.pdf (accessed 11.2.24).

ASPCA, 2016. Guide to trap-neuter-return and colony care [WWW Document]. Alley Cat Allies, American Society for the Prevention of Cruelty to Animals (ASPCA), and Mayor's Alliance for NYC's Animals. URL https://aspcapro.org/sites/default/files/TNR_workshop_handbook.3.pdf. (accessed 11.2.24).

Babaahmadifooladi, M., Jacxsens, L., Van de Wiele, T., Laing, G. Du, 2020. Gap analysis of nickel bioaccessibility and bioavailability in different food matrices and its impact on the nickel exposure assessment. Food Res. Int. https://doi.org/10.1016/j.foodres.2019.108866.

Backer, L.C., Grindem, C.B., Corbett, W.T., Cullins, L., Hunter, J.L., 2001. Pet dogs as sentinels for environmental contamination. Sci. Total Environ. 274, 161–169.

Baptista, J., Seixas, C., Gonzalo-Orden, F.M., Oliveira, J.M., 2024. How to design a biomonitoring Study-A practical guide for veterinary professionals under a one health approach. World Vet. J. 14, 461–463. https://doi.org/10.54203/scil.2024.wvj53.

Bedi, M., Sapozhnikova, Y., Ng, C., 2024. Evaluating contamination of seafood purchased from U.S. retail stores by persistent environmental pollutants, pesticides and veterinary drugs. Food Addit. Contam. 41. https://doi.org/10.1080/19440049.2024.2310128.

Bertero, A., Fossati, P., Caloni, F., 2020. Indoor poisoning of companion animals by chemicals. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2020.139366.

BOE, 2023. Ley 7/2023, de protección de los derechos y el bienestar de los animales. Boletín Oficial del Estado de 8 de marzo 75, 45618–45671.

Brouziotis, A.A., Giarra, A., Libralato, G., Pagano, G., Guida, M., Trifuoggi, M., 2022. Toxicity of rare earth elements: an overview on human health impact. Front. Environ. Sci. https://doi.org/10.3389/fenvs.2022.948041.

Buchweitz, J.P., Drankhan, H.R., Lehner, A.F., 2019. Blood arsenic concentrations in felids. Vet. Rec. 185. https://doi.org/10.1136/vr.105242.
Buser, M.C., Ingber, S.Z., Raines, N., Fowler, D.A., Scinicariello, F., 2016. Urinary and blood cadmium and lead and kidney function: NHANES 2007-2012. Int. J. Hyg Environ. Health 219. https://doi.org/10.1016/j.ijheh.2016.01.005.
Buxaderas, S.C., Farré-Rovira, R., 1985. Whole blood and serum zinc levels in relation to sex and age. Rev. Esp. Fisiol. 41.
Chen, Y., Xu, X., Zeng, Z., Lin, X., Qin, Q., Huo, X., 2019. Blood lead and cadmium levels associated with hematological and hepatic functions in patients from an e-waste-polluted area. Chemosphere 220. https://doi.org/10.1016/j.chemosphere.2018.12.129.
Dulsat-Masvidal, M., Lourenço, R., Lacorte, S., D'Amico, M., Albayrak, T., Andevski, J., Aradis, A., Baltag, E., Berger-Tal, O., Berny, P., Choresh, Y., Duke, G., Espín, S., García-Fernández, A.J., Gómez-Ramírez, P., Hallgrimsson, G.T., Jaspers, V., Johansson, U., Kovacs, A., Krone, O., Leivits, M., Martínez-López, E., Mateo, R., Movalli, P., Sánchez-Virosta, P., Shore, R.F., Valkama, J., Vrezec, A., Xirouchakis, S., Walker, L.A., Wernham, C., 2021. A review of constraints and solutions for collecting raptor samples and contextual data for a European raptor biomonitoring facility. Sci. Total Environ. 793. https://doi.org/10.1016/j.scitotenv.2021.148599.
EC, 2019. Analytical Quality Control and Method Validation for Pesticide Residues Analysis in Food and Feed (SANTE/12682/201S9), Sante/12682/2019.
Escher, B.I., Stapleton, H.M., Schymanski, E.L., 2020. Tracking complex mixtures of chemicals in our changing environment. Science. https://doi.org/10.1126/science.aay6636 (1979).
Espín, S., García-Fernández, A.J., Herzke, D., Shore, R.F., van Hattum, B., Martínez-López, E., Coeurdassier, M., Eulaers, I., Fritsch, C., Gómez-Ramírez, P., Jaspers, V.L.B., Krone, O., Duke, G., Helander, B., Mateo, R., Movalli, P., Sonne, C., van den Brink, N.W., 2016. Tracking pan-continental trends in environmental contamination using sentinel raptors—what types of samples should we use? Ecotoxicology. https://doi.org/10.1007/s10646-016-1636-8.
Esposito, M., De Roma, A., Maglio, P., Sansone, D., Picazio, G., Bianco, R., De Martinis, C., Rosato, G., Baldi, L., Gallo, P., 2019. Heavy metals in organs of stray dogs and cats from the city of Naples and its surroundings (Southern Italy). Environ. Sci. Pollut. Control Ser. 26. https://doi.org/10.1007/s11356-018-3838-5.
European Commission, 2019. Analytical Quality Control and Method Validation for Pesticide Residues Analysis in Food and Feed (SANTE/12682/2019), Sante/12682/2019.
Fascetti, A.J., Rogers, Q.R., Morris, J.G., 2002. Blood copper concentrations and cuproenzyme activities in a colony of cats. Vet. Clin. Pathol. 31. https://doi.org/10.1111/j.1939-165X.2002.tb00299.x.
González-Antuña, A., Camacho, M., Henríquez-Hernández, L.A., Boada, L.D., Almeida-González, M., Zumbado, M., Luzardo, O.P., 2017. Simultaneous quantification of 49 elements associated to e-waste in human blood by ICP-MS for routine analysis. MethodsX 4. https://doi.org/10.1016/j.mex.2017.10.001.
Hegedus, C., Andronie, L., Uiuiu, P., Jurco, E., Lazar, E.A., Popescu, S., 2023. Pets, genuine tools of environmental pollutant detection. Animals. https://doi.org/10.3390/ani13182923.
Henríquez-Hernández, L.A., Montero, D., Camacho, M., Ginés, R., Boada, L.D., Ramírez Bordón, B., Valerón, P.F., Almeida-González, M., Zumbado, M., Haroun, R., Luzardo, O.P., 2017. Comparative analysis of selected semi-persistent and emerging pollutants in wild-caught fish and aquaculture associated fish using Bogue (Boops boops) as sentinel species. Sci. Total Environ. 581–582. https://doi.org/10.1016/j.scitotenv.2016.12.107.
Igbokwe, I.O., Igwenagu, E., Igbokwe, N.A., 2020. Aluminium toxicosis: a review of toxic actions and effects. Interdiscip. Toxicol. 12. https://doi.org/10.2478/intox-2019-0007.
Jensen, A.L., Vestergaard, J.D., Nielsen, L.N., Krogh, A.K.H., Langhorn, R., 2025. In vitro-induced Heinz bodies showed no impact on feline reticulocyte haemoglobin content measurement using the Advia 2120i analyser. J. Feline Med. Surg. 27. https://doi.org/10.1177/1098612X251314709.
Jensen, H.A., Meilby, H., Nielsen, S.S., Sandøe, P., 2022. Movement patterns of roaming companion cats in denmark—A study based on GPS tracking. Animals 12. https://doi.org/10.3390/ani12141748.
Kučera, J., Byrne, A.R., Mravcová, A., Lener, J., 1992. Vanadium levels in hair and blood of normal and exposed persons. Sci. Total Environ. 115. https://doi.org/10.1016/0048-9697(92)90329-Q. The.
Kunath, T., Kather, S., Dengler, F., Nexo, E., Pfannkuche, H., Heilmann, R.M., 2024. Serum transcobalamin concentration in cats—method validation and evaluation in chronic enteropathies and other conditions. Vet. Sci. 11, 552. https://doi.org/10.3390/VETSCI11110552/S1.
Lázaro, C., Castillo-Contreras, R., Sánchez-García, C., 2024. Free-roaming domestic cats in natura 2000 sites of central Spain: home range, distance travelled and management implications. Appl. Anim. Behav. Sci. 270. https://doi.org/10.1016/j.applanim.2023.106136.
Lee, S.J., Mamun, M., Atique, U., An, K.G., 2023. Fish tissue contamination with organic pollutants and heavy metals: link between land use and ecological health. Water (Switzerland) 15. https://doi.org/10.3390/w15101845.
Luzardo, O.P., Hansen, A., Martín-Cruz, B., Macías-Montes, A., Travieso-Aja, M. del M., 2025a. Integrating conservation and community engagement in free-roaming cat management: a case study from a natura 2000 protected area. Animals 15, 429. https://doi.org/10.3390/ANI15030429/S1.
Luzardo, O.P., Manzanares-Fernández, R., Becerra-Carollo, J.R., Travieso-Aja, M. del M., 2025b. Territorially stratified modeling for sustainable management of free-roaming cat populations in Spain: a national approach to urban and rural environmental planning. Animals 15, 2278. https://doi.org/10.3390/ANI15152278/S1.
Macías-Montes, A., Zumbado, M., Luzardo, O.P., Rodríguez-Hernández, Á., Acosta-Dacal, A., Rial-Berriel, C., Boada, L.D., Henríquez-Hernández, L.A., 2021. Nutritional evaluation and risk assessment of the exposure to essential and toxic elements in dogs and cats through the consumption of pelleted dry food: how important is the quality of the feed? Toxics 9, 133. https://doi.org/10.3390/TOXICS9060133/S1.
Matus, P., Urquidi, C., Cárcamo, M., Vidal, V., 2024. Integrating the exposome and one health approach to national health surveillance: an opportunity for Latin American countries in health preventive management. Front. Public Health 12, 1376609. https://doi.org/10.3389/FPUBH.2024.1376609/BIBTEX.
Medina, F.M., Nogales, M., 2009. A review on the impacts of feral cats (Felis silvestris catus) in the Canary Islands: implications for the conservation of its endangered fauna. Biodivers. Conserv. 18, 829–846. https://doi.org/10.1007/S10531-008-9503-4/TABLES/2.
Milne, D.B., Sims, R.L., Ralston, N.V.C., 1990. Manganese content of the cellular components of blood. Clin. Chem. 36. https://doi.org/10.1093/clinchem/36.3.450.
Möckel, S., 2022. Natura 2000-sites: legal requirements for agricultural and forestry land-use. Nat. Conserv. 48, 161–184. https://doi.org/10.3897/NATURECONSERVATION.48.77899, 161-184 48.
Mortensen, M.E., Caudill, S.P., Caldwell, K.L., Ward, C.D., Jones, R.L., 2014. Total and methyl mercury in whole blood measured for the first time in the U.S. population: NHANES 2011-2012. Environ. Res. 134. https://doi.org/10.1016/j.envres.2014.07.019.
Pagano, G., Guida, M., Tommasi, F., Oral, R., 2015. Health effects and toxicity mechanisms of rare earth elements—Knowledge gaps and research prospects. Ecotoxicol. Environ. Saf. 115, 40–48. https://doi.org/10.1016/J.ECOENV.2015.01.030.
Philippe-Lesaffre, M., Lusardi, L., Castañeda, I., Bonnaud, E., 2024. Intrinsic and extrinsic drivers of home range size in owned domestic cats Felis catus: insights from a French suburban study. Conserv. Sci. Pract. 6. https://doi.org/10.1111/csp2.13066.
Piontek, A.M., Wojtylak-Jurkiewicz, E., Schmidt, K., Gajda, A., Lesiak, M., Wierzbowska, I.A., 2021. Analysis of cat diet across an urbanisation gradient. Urban Ecosyst. 24. https://doi.org/10.1007/s11252-020-01017-y.
Pourchet, M., Debrauwer, L., Klanova, J., Price, E.J., Covaci, A., Caballero-Casero, N., Oberacher, H., Lamoree, M., Damont, A., Fenaille, F., Vlaanderen, J., Meijer, J., Krauss, M., Sarigiannis, D., Barouki, R., Le Bizec, B., Antignac, J.P., 2020. Suspect and non-targeted screening of chemicals of emerging concern for human biomonitoring, environmental health studies and support to risk assessment: from promises to challenges and harmonisation issues. Environ. Int. 139. https://doi.org/10.1016/j.envint.2020.105545.
Primost, M.A., Chierichetti, M.A., Castaños, C., Bigatti, G., Miglioranza, K.S.B., 2024. Persistent organic pollutants (POPs), current use pesticides (CUPs) and polycyclic aromatic hydrocarbons (PAHs) in edible marine invertebrates from a Patagonian harbor. Mar. Pollut. Bull. 207, 116940. https://doi.org/10.1016/J.MARPOLBUL.2024.116940.
Reynolds, B.S., Concordet, D., Germain, C.A., Daste, T., Boudet, K.G., Lefebvre, H.P., 2010. Breed dependency of reference intervals for plasma biochemical values in cats. J. Vet. Intern. Med. 24. https://doi.org/10.1111/j.1939-1676.2010.0541.x.
Rial-Berriel, C., Acosta-Dacal, A., González, F., Pastor-Tiburón, N., Zumbado, M., Luzardo, O.P., 2020a. Supporting dataset on the validation and verification of the analytical method for the biomonitoring of 360 toxicologically relevant pollutants in whole blood. Data Brief. https://doi.org/10.1016/j.dib.2020.105878.
Rial-Berriel, C., Acosta-Dacal, A., Zumbado, M., Luzardo, O.P., 2020b. Micro QuEChERS-based method for the simultaneous biomonitoring in whole blood of 360 toxicologically relevant pollutants for wildlife. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2020.139444.
Rodil, R., Villaverde-de-Sáa, E., Cobas, J., Quintana, J.B., Cela, R., Carro, N., 2019. Legacy and emerging pollutants in marine bivalves from the Galician coast (NW Spain). Environ. Int. 129. https://doi.org/10.1016/j.envint.2019.05.018.
Rodríguez-Hernández, Á., Camacho, M., Henríquez-Hernández, L.A., Boada, L.D., Ruiz-Suárez, N., Valerón, P.F., Almeida González, M., Zaccaroni, A., Zumbado, M., Luzardo, O.P., 2016. Assessment of human health hazards associated with the dietary exposure to organic and inorganic contaminants through the consumption of fishery products in Spain. Sci. Total Environ. 557–558. https://doi.org/10.1016/j.scitotenv.2016.03.035.
Ru, X., Yang, L., Shen, G., Wang, K., Xu, Z., Bian, W., Zhu, W., Guo, Y., 2024. Microelement strontium and human health: comprehensive analysis of the role in inflammation and non-communicable diseases (NCDs). Front. Chem. 12, 1367395. https://doi.org/10.3389/FCHEM.2024.1367395/FULL.
Ruiz-Suárez, N., Camacho, M., Boada, L.D., Henríquez-Hernández, L.A., Rial, C., Valerón, P.F., Zumbado, M., González, M.A., Luzardo, O.P., 2015. The assessment of daily dietary intake reveals the existence of a different pattern of bioaccumulation of chlorinated pollutants between domestic dogs and cats. Sci. Total Environ. 530–531, 45–52. https://doi.org/10.1016/j.scitotenv.2015.05.070.
Schmidt, P.L., 2009. Companion animals as sentinels for public health. Vet. Clin. N. Am. Small Anim. Pract. https://doi.org/10.1016/j.cvsm.2008.10.010.
Schultze, B., Lind, P.M., Larsson, A., Lind, L., 2014. Whole blood and serum concentrations of metals in a Swedish population-based sample. Scand. J. Clin. Lab. Invest. 74. https://doi.org/10.3109/00365513.2013.864785.
Sedláčková, K., Száková, J., Načeradská, M., Praus, L., Tlustoš, P., 2022. Essential microelement (copper, selenium, zinc) status according to age and sex in healthy cats. Acta Vet. Hung. 70. https://doi.org/10.1556/004.2022.00036.
Solomon, N.G., Scheetz, T., McCay, S., Crist, T.O., Keane, B., 2025. Influence of food distribution and relatedness on social interactions in a colony of free-ranging domestic cats (Felis catus). Ethology 131, e13564. https://doi.org/10.1111/ETH.13564. WGROUP:STRING:PUBLICATION.

Spanish Directorate of Animal Rights, 2024. Directriz técnica de la dirección general de derechos de los animales sobre gestión de poblaciones felinas [WWW Document]. Spanish Ministry of Social Rights and 2030 Agenda. URL https://www.agenda2030.gob.es/derechos-animales/colonias-felinas/docs/DGDA.pdf. (accessed 10.31.24).

Tansel, B., 2017. From electronic consumer products to e-wastes: global outlook, waste quantities, recycling challenges. Environ. Int. 98, 35–45. https://doi.org/10.1016/J.ENVINT.2016.10.002.

Tietz, T., Lenzner, A., Kolbaum, A.E., Zellmer, S., Riebeling, C., Gürtler, R., Jung, C., Kappenstein, O., Tentschert, J., Giulbudagian, M., Merkel, S., Pirow, R., Lindtner, O., Tralau, T., Schäfer, B., Laux, P., Greiner, M., Lampen, A., Luch, A., Wittkowski, R., Hensel, A., 2019. Aggregated aluminium exposure: risk assessment for the general population. Arch. Toxicol. https://doi.org/10.1007/s00204-019-02599-z.

Todd, S.E., Thomas, D.G., Hendriks, W.H., 2012. Selenium balance in the adult cat in relation to intake of dietary sodium selenite and organically bound selenium. J. Anim. Physiol. Anim. Nutr. 96. https://doi.org/10.1111/j.1439-0396.2011.01132.x.

Trenholme, H.N., Tynan, B., Jackson, M., Kerl, M., 2022. Comparison of point-of-care NOVA CCX blood gas analyzer to laboratory analyzer in a population of healthy adult cats. J. Vet. Emerg. Crit. Care 32. https://doi.org/10.1111/vec.13155.

van den Broek, D.H.N., Chang, Y.M., Elliott, J., Jepson, R.E., 2018. Prognostic importance of plasma total magnesium in a cohort of cats with azotemic chronic kidney disease. J. Vet. Intern. Med. 32. https://doi.org/10.1111/jvim.15141.

Wang, Y., Jiao, Y., Kong, Q., Zheng, F., Shao, L., Zhang, T., Jiang, D., Gao, X., 2021. Occurrence of polycyclic aromatic hydrocarbons in fried and grilled fish from Shandong China and health risk assessment. Environ. Sci. Pollut. Control Ser. 28. https://doi.org/10.1007/s11356-021-13045-y.

Watt, J.A.J., Burke, I.T., Edwards, R.A., Malcolm, H.M., Mayes, W.M., Olszewska, J.P., Pan, G., Graham, M.C., Heal, K.V., Rose, N.L., Turner, S.D., Spears, B.M., 2018. Vanadium: a Re-Emerging environmental hazard. Environ. Sci. Technol. 52, 11973–11974. https://doi.org/10.1021/ACS.EST.8B05560.

Yao, X., Steven Xu, X., Yang, Y., Zhu, Zhi, Zhu, Zhao, Tao, F., Yuan, M., 2021. Stratification of population in NHANES 2009–2014 based on exposure pattern of lead, cadmium, mercury, and arsenic and their association with cardiovascular, renal and respiratory outcomes. Environ. Int. 149. https://doi.org/10.1016/j.envint.2021.106410.