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Review

# Animals as Sentinels of Environmental Toxicity in Italy: A Systematic Review of Epidemiological and Ecotoxicological Linkages under a One Health Framework

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## Abstract

The "Sentinel Hypothesis" posits that animals often manifest the effects of environmental pollution earlier than humans. This systematic review quantitatively validates this hypothesis within the One Health framework, focusing on three Italian National Interest Sites for Remediation (SINs): Taranto, Campania's "Terra dei Fuochi," and Sardinia. Adhering to PRISMA guidelines, we synthesized data from 76 studies (43 human epidemiological/biomonitoring outcomes, 33 animal sentinel outcomes). In Taranto, excess human cancer incidence (e.g., +40% liver cancer in men) correlates with severe dioxin contamination in the mussel *Mytilus galloprovincialis* (up to 14.88 pg WHO-TEQ/g). In Campania, polychlorinated biphenyls (PCBs) and dioxins detected in livestock products mirrored contamination found in human breast milk and elevated cancer mortality. In Sardinia, while human cancer epidemiology remains debated, lead accumulation in wild boar (*Sus scrofa*) liver (mean 6.70 mg/kg) aligns with elevated lead levels in children's hair, highlighting risks from both mining legacies and hunting ammunition. The findings confirm that veterinary surveillance data frequently precede human health alerts, documenting a "systematic delay" in public health response. We recommend integrating veterinary and human surveillance systems to operationalize animal sentinels as early warning tools for environmental health.

## Keywords

Biomonitoring, Environmental pollution, Italy, Public health, One Health, Sentinel species

# Introduction: A Paradigm Shift in Environmental Toxicology

## The Evolution of the One Health Framework

The conceptual framework of "One Health," formally endorsed and promoted by the Quadripartite alliance—comprising the Food and Agriculture Organization (FAO), the United Nations Environment Programme (UNEP), the World Health Organisation (WHO), and the World Organisation for Animal Health (WOAH)—has fundamentally reshaped the global approach to health security. Historically, the operationalisation of One Health was predominantly zoonotic-centric, emerging as a direct response to the spillover events of infectious pathogens such as Avian Influenza, Ebola, and SARS. This classical view prioritised the interface between wildlife reservoirs, domestic livestock, and human populations primarily as a conduit for viral and bacterial transmission.

However, the Anthropocene epoch has necessitated a profound maturation of this paradigm. The modern application of One Health has expanded beyond the "germ theory" of cross-species transmission to fully integrate environmental



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and ecosystem health as a co-equal and foundational pillar (FAO et al., 2022). This evolution recognises that chemical, radiological, and physical pollutants disregard species barriers just as effectively as pathogens. In this context, the shared environment becomes the vector. The air we breathe, the aquifers we tap, and the soil that sustains our agriculture act as a common medium of exposure for all biological organisms inhabiting a specific territory. Consequently, the health status of animal populations is not merely a veterinary concern but a mirror reflecting the toxicological burden of the ecosystem that sustains human life.

This expanded perspective is critical when addressing the chronic, low-dose exposure scenarios typical of industrialised nations. While infectious outbreaks are acute and immediately visible, environmental toxicity is often insidious, cumulative, and multi-generational. The One Health approach, therefore, must pivot to include "toxicological sentinels"—animals whose biological responses to environmental contaminants provide early warnings of risks that may eventually manifest in human populations.

## The Sentinel Hypothesis and the Phenomenon of Systematic Delay

The "Sentinel Hypothesis" is predicated on the physiological and ecological reality that domestic and wild animals often serve as more sensitive, or temporally advanced, indicators of environmental hazards than human populations (Afzal & Mahreen, 2024). This heightened sensitivity arises from several biological and behavioural factors: animals often possess shorter lifespans, higher metabolic rates, and more direct interaction with environmental media (e.g., soil ingestion in grazing livestock, bioaccumulation in filter-feeding molluscs). As a result, they frequently manifest the pathological effects of pollution—ranging from acute toxicosis to teratogenic defects and neoplasms—significantly earlier than co-located human cohorts.

Despite the intuitive logic of this hypothesis, the history of environmental epidemiology is marred by a phenomenon of "systematic delay." This refers to the recurrent temporal lag, often spanning years or decades, between the manifestation of toxicological signs in animal populations and the recognition of the corresponding threat to human public health. This delay represents a failure of primary prevention, where the predictive warning signal offered by animal sentinels is either ignored, compartmentalised within veterinary silos, or disconnected from human medical surveillance.

Historical precedents illustrate this systemic failure vividly. In the Minamata disaster of the 1950s, the local cat population exhibited severe neurobehavioural ataxia—colloquially termed "dancing cat fever"—long before the diagnosis of methylmercury poisoning in the human fishing community. Similarly, during the Seveso industrial accident of 1976 in Italy, the mass mortality of domestic poultry and rabbits in the fallout zone provided an immediate biological alarm of dioxin (TCDD) toxicity days before the first cases of chloracne were diagnosed in children (Bertazzi, 1991), yet the evacuation was delayed as authorities debated the chemical nature of the cloud. These examples underscore a critical missed opportunity: in each case, the animal sentinel served as a functional biological alarm that, had it been integrated into a responsive human health surveillance system, could have mitigated human exposure.

The primary objective of this systematic review is to synthesise and assess the quantitative evidence linking human epidemiological outcomes with co-located animal sentinel biomonitoring data in Italy's major "Sites of National Interest for Remediation" (SINs). Specifically, we aim to determine whether veterinary surveillance data currently collected by local authorities could have predicted, or can currently explain, the excess morbidity and mortality observed in these human populations. The conceptual framework underpinning this review is illustrated in Figure 1.



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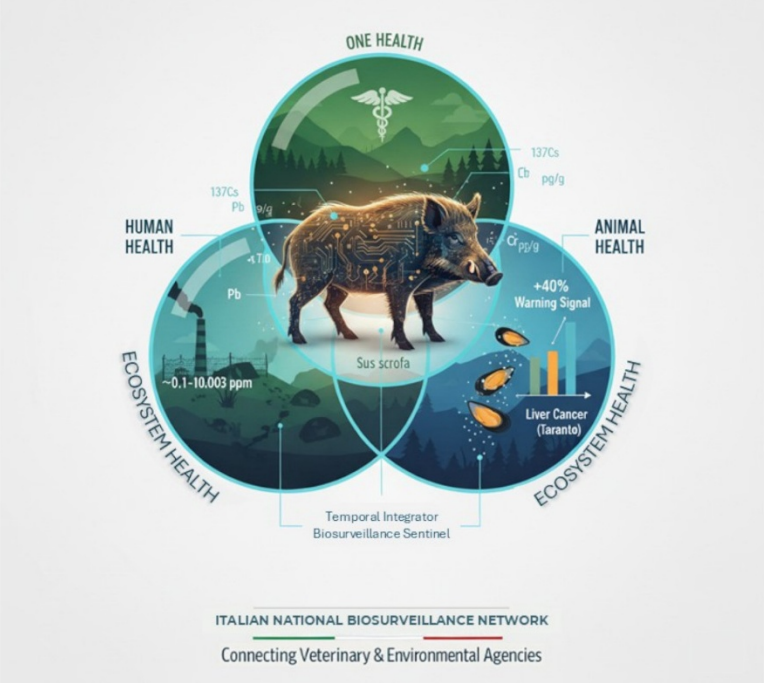


**Figure** 1. A Conceptual Model of the "One Health" Sentinel Hypothesis. This diagram visualises the review's central thesis, illustrating how animal sentinels (such as *Sus scrofa* or *Mytilus galloprovincialis*) act as temporal integrators of environmental contamination with respect to ecosystem health. It shows how the health status of these animals (Animal Health, O2) provides a quantitative and predictive warning signal for human epidemiological outcomes (Human Health, O1), such as the liver cancer excesses observed in Taranto.

# *Methods: A Systematic Framework for One Health Assessment*

## Methodological Adherence

This systematic review was conducted and reported in strict accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 guidelines (Page et al., 2021). To ensure a focused and quantitative assessment of the Sentinel Hypothesis, the research question and inclusion strategy were defined *a priori* using the PICO (Population, Intervention, Comparison, Outcome) framework:

**Population (P):** The study focuses on dual populations sharing specific geographic envelopes: Human populations residing in the Italian SINs of Taranto (industrial pollution), Campania "Terra dei Fuochi" (illegal waste disposal), and Sardinia (mining and military fallout); and co-located sentinel animal species including, but not limited to, the Mediterranean mussel (*Mytilus galloprovincialis*), wild boar (*Sus scrofa*), and domestic livestock (bovine, bubaline, ovine).

**Intervention/Exposure (I):** Chronic environmental exposure to a defined spectrum of anthropogenic contaminants. This includes Persistent Organic Pollutants (POPs) such as dioxins (PCDD/Fs) and polychlorinated biphenyls (PCBs); heavy metals including lead (Pb), cadmium (Cd), chromium (Cr), and arsenic (As); and radionuclides (e.g., depleted uranium, thorium).

**Comparison (C):** For human outcomes, the comparison is made against national or regional reference populations to generate Standardised Mortality/Incidence Ratios (SMR/SIR). For animal outcomes, comparisons are made against established European Union food safety limits (e.g., EC Regulation 1881/2006) or background environmental levels.

**Outcome (O):** The review strictly selected for quantitative metrics.

**O1 (Human Outcome):** Epidemiological indicators including SMR, SIR, hazard ratios (HR), and quantitative human biomonitoring data (concentrations in blood, hair, and breast milk).

**O2 (Sentinel Outcome):** Quantified contaminant concentrations in animal tissues (liver, muscle, kidney) or products (milk, eggs), expressed in standard units (e.g., pg WHO-TEQ/g, mg/kg).



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## Search Strategy and Data Sources

A systematic literature search was executed to identify studies published up to October 2025. The search strategy utilised Boolean logic to intersect geographic terms, contaminant classes, and sentinel/health keywords. The primary databases queried were PubMed, Scopus, and Web of Science.

To ensure comprehensive coverage of "grey literature" and official government data— which is, often where veterinary monitoring data reside—the search was supplemented by targeted queries of institutional repositories. Specifically, reports from the *Istituto Superiore di Sanità* (ISS), particularly the SENTIERI project (Epidemiological Study of Residents in National Priority Contaminated Sites), and data from the *Istituti Zooprofilattici Sperimentali* (IZS) and *Agenzie Regionali per la Protezione dell'Ambiente* (ARPA) were prioritised. These institutes operate within the national network of Competent Authorities and Official Laboratories responsible for environmental monitoring and official controls on food and animal health in Italy. Their annual reports and specific monitoring plans (e.g.,*Piano Nazionale Residui*) contain high-fidelity quantitative data that often do not reach peer-reviewed journals immediately.

The search string structure was constructed as reported below:

(("Taranto"[tiab] OR "Campania"[tiab] OR "Terra dei Fuochi"[tiab] OR "Quirra"[tiab] OR "Sardinia"[tiab] OR "SENTIERI"[tiab]) AND (("dioxin"[tiab] OR "dioxins"[tiab] OR "PCB"[tiab] OR "PCBs"[tiab] OR "persistent organic pollutant*"[tiab] OR "heavy metal*"[tiab] OR "lead"[tiab] OR "cadmium"[tiab] OR "chromium"[tiab] OR "radionuclide*"[tiab] OR "cesium"[tiab] OR "depleted uranium"[tiab])) AND (("SMR"[tiab] OR "Standardized Mortality Ratio"[tiab] OR "SIR"[tiab] OR "Standardized Incidence Ratio"[tiab] OR "epidemiolog*"[tiab] OR "Mytilus"[tiab] OR "Sus scrofa"[tiab] OR "wild boar"[tiab] OR "animal sentinel"[tiab] OR "biomonitoring"[tiab] OR "livestock"[tiab]))

This strategy yielded a total of 509 records (61 from PubMed, 165 from Scopus, and 283 from Web of Science).

## Selection and Data Extraction

Following the deduplication of 86 records, the remaining 423 records were screened by title and abstract. This process led to the full-text assessment of 78 articles. Two reviewers independently extracted data, reconciling discrepancies through consensus. Inclusion was strictly limited to studies presenting primary quantitative data. Narrative reviews, editorials, and studies utilising non-animal bioindicators (e.g., mosses, lichens) were excluded to maintain the focus on the phylogenetic proximity of the One Health animal-human link.

Ultimately, 76 studies met the full inclusion criteria. These comprised forty-three studies focusing on human outcomes (O1) and thirty-three studies focusing on animal sentinel outcomes (O2). It is noted that while the text references 76 distinct studies, the summary tables provided in the Results section aggregate these into key representative findings to avoid redundancy. For instance, multiple annual monitoring reports of the same mussel beds in Taranto or repeated SENTIERI updates for Campania were grouped to present the most robust and representative quantitative values. The study selection process is summarised in the PRISMA flow diagram (Figure 2).



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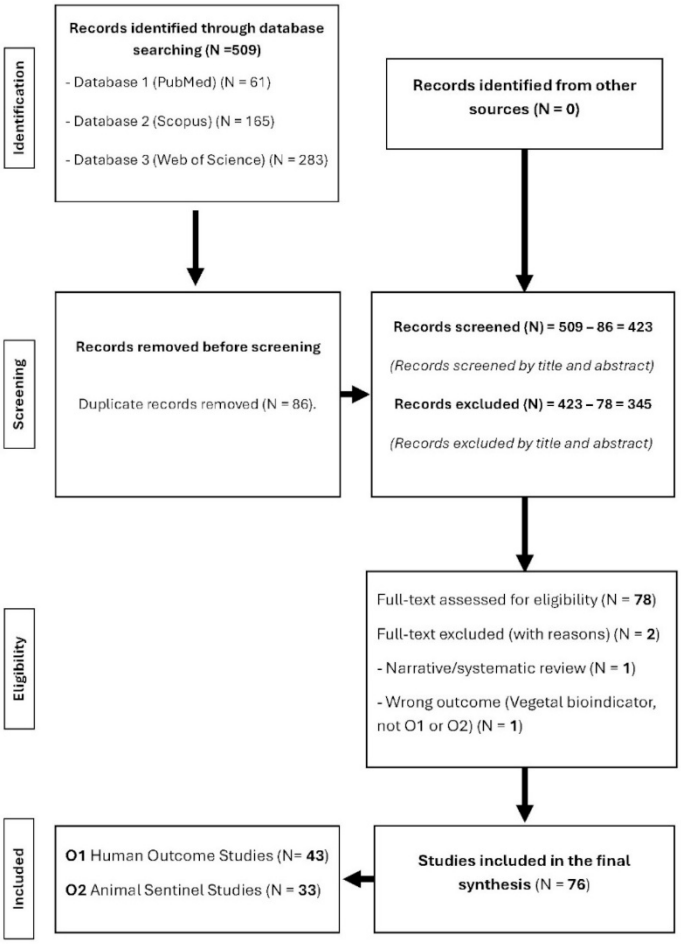


**Figure** 2. PRISMA flow diagram of the study selection process. The diagram documents the flow of records, beginning with the 509 records identified through database searching. After duplicate removal (n = 86), 423 records were screened by title and abstract, leading to the assessment of 78 full-text articles for eligibility. Seventy-six studies (43 O1 human, 33 O2 animal) met the full inclusion criteria and were included in the final synthesis.

## *Results: The Convergence of Veterinary and Human Evidence*

The analysis of the included studies reveals a striking convergence between environmental contamination detected in animal sentinels and adverse health outcomes in human populations. The results are presented by geographic case study to facilitate a direct comparison of O1 and O2 data.

## Case Study: Taranto – The Industrial Burden

The Taranto SIN is dominated by the former ILVA steelworks (now Acciaierie d'Italia), one of the largest in Europe, alongside a refinery and a cement plant. The pollution profile is characterised by heavy industrial emissions, particularly dioxins, PCBs, and heavy metals, which settle into the surrounding soil and the adjacent marine basins of the Mar Piccolo and Mar Grande.

### Human Epidemiological Outcomes (O1)

The human health impact in Taranto has been exhaustively documented by the SENTIERI project and independent researchers. The epidemiological data reveal a pattern of morbidity and mortality consistent with chronic exposure to industrial pollutants (Ancona et al., 2014; Pirastu et al., 2011).

**Cancer Incidence (SIR):** Data from the Taranto Cancer Registry, synthesised by the ISS, indicate statistically significant excesses in cancer incidence. Men residing in the SIN exhibit a **+40% excess** in the Standardised Incidence Ratio (SIR) for liver cancer, while women show a **+24% excess** for breast cancer (Pirastu et al., 2014).



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These specific cancer types are biologically consistent with exposure to endocrine-disrupting chemicals and hepatotoxic agents like dioxins.

**Mortality (HR):** Longitudinal cohort studies have reinforced these findings. A recent analysis identified a hazard ratio (HR) of **1.22** for breast cancer mortality among women residing in the contaminated area (Giannico et al., 2024). Furthermore, vulnerable subpopulations, such as dementia patients residing in the SIN, show an elevated all-cause mortality risk (HR 1.25), suggesting that environmental stress exacerbates underlying frailty (Mincuzzi et al., 2024).

**Biomonitoring:** Direct evidence of exposure is provided by human biomonitoring. Residents exhibit elevated urinary concentrations of arsenic (As) and chromium (Cr), and women living in the hotspot areas show measurable serum levels of dioxins and PCBs, confirming that the epidemiological excesses are rooted in internal dose exposure (Vimercati et al., 2017; Miniero et al., 2025).

### Animal Sentinel Outcomes (O2)

The veterinary surveillance data from Taranto provides a mechanistic explanation for the human exposure pathways, particularly through the marine food web.

**Marine Sentinels (*Mytilus galloprovincialis*):** The Mediterranean mussel, cultivated extensively in the Mar Piccolo of Taranto, act as a potent bio accumulator. A seven-year longitudinal study (2014-2020) reported median dioxin and dioxin-like PCB concentrations of **6.5 pg WHO-TEQ/g**, with peak values reaching **14.88 pg WHO-TEQ/g** (Giannico et al., 2022). These levels frequently exceed the European Union food safety limit (6.5 pg/g), necessitating repeated harvesting bans. The mussel data act as a temporal integrator of water quality, revealing pulses of contamination that might be missed by sporadic water sampling.

**Heavy Metals:** In addition to organic pollutants, mussels and other marine species like the red mullet (*Mullus barbatus*) and limpets (*Patella caerulea*) have demonstrated significant bioaccumulation of lead (Pb), cadmium (Cd), and chromium (Cr) (Lionetto et al., 2004; Cardellicchio et al., 2008). Specifically, red mullet samples showed high chromium levels (0.47–0.97 µg/g ww), indicating bioavailability of metals in the benthic ecosystem.

## Case Study: Campania – The "Terra dei Fuochi"

The "Land of Fires" refers to a vast area between Naples and Caserta plagued by decades of illegal hazardous waste disposal and open-air incineration. The contamination is diffuse, affecting soil and groundwater, distinguishing it from the point-source pollution of Taranto.

### Human Epidemiological Outcomes (O1)

**Mortality (SMR):** The source of epidemiological data was represented by the SENTIERI project, which identified severe excesses in cancer mortality. Forty-three studies confirmed that men in the area exhibit a Standardised Mortality Ratio (SMR) of **115** (90% CI: 105–127) for laryngeal cancer and **110.7** (90% CI: 105–117) for bladder cancer (Pirastu et al., 2011). These excesses are statistically significant and correlate spatially with areas of known illegal dumping.

**Biomonitoring:** The SEBIOREC study and others have confirmed widespread population exposure. High levels of PCBs and dioxins have been detected in human breast milk, indicating long-term bioaccumulation of lipophilic toxins. Additionally, children living in urbanised areas of the SIN showed significantly higher blood lead levels (**60.0 ± 3.0 µg/L**) compared to rural controls (40.0 ± 2.0 µg/L), highlighting the paediatric burden of the waste crisis (Perrone et al., 1999).

### Animal Sentinel Outcomes (O2)

Contradicting the notion that the waste crisis was solely an aesthetic or legal issue, O2 data confirms the entry of toxins into the food chain.

**Terrestrial Sentinels (Livestock):** Dioxins and PCBs were detected in buffalo milk and cow's milk (Esposito et al., 2009). Crucially, studies utilised the levels in milk to back-calculate and predict soil contamination levels, validating the sentinel utility of grazing animals (Perugini et al., 2012). The buffalo, grazing on potentially contaminated forage, acts as a sampler of the wider environment.



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**Bioaccumulation:** Free-range hen eggs were found to contain heavy metals (Cd, Cr, Pb) and traces of organic pollutants (Esposito et al., 2016). Hen eggs are particularly valuable sentinels for "micro-environments" such as backyards, providing high-resolution spatial data on soil contamination that broader air monitoring might miss.

**Marine Sentinels:** The pollution plume extends to the Gulf of Naples, where *Mytilus galloprovincialis* samples have recorded PCB levels ranging from 56.8 to an extreme **47,909.5 ng/g**, illustrating the massive transport of terrestrial waste into the marine ecosystem via runoff and illegal dumping in waterways (Naso et al., 2005).

## 3.3 Case Study: Sardinia – The Challenge of Spatial Complexity

Sardinia presents a complex toxicological landscape. It hosts the Salto di Quirra Interforce Test Range (PISQ) in the southeast, the historic Sulcis-Iglesiente mining district in the southwest, and various industrial zones. The interpretation of sentinel data here requires a nuanced understanding of these distinct, though sometimes overlapping, pollution sources.

### Human Epidemiological Outcomes (O1)

**Quirra (Military):** The "Quirra Syndrome" involved suspected clusters of haemolymphopoietic cancers and birth defects linked to military testing (e.g., thorium, depleted uranium). However, formal epidemiological reviews have been described as "uncertain" or inconclusive regarding a generalised cancer excess. Some studies found excess myeloma mortality (SMR based on 5 observed cases vs 2.3 expected), while others failed to confirm clusters of leukaemia (Cocco, 2012). This uncertainty often stems from small population sizes and the difficulty of exposure reconstruction.

**Sulcis (Mining):** In the mining districts of the southwest, the link is clearer. Human biomonitoring has confirmed elevated lead (Pb) levels in the hair of children living near abandoned mines, directly correlating with the geogenic and anthropogenic load of the environment (Varrica et al., 2014). This provides a direct O1 measure of environmental absorption.

**Neurological Outcomes:** A high prevalence of multiple sclerosis in south-western Sardinia has been spatially associated with heavy metal exposure in soils and water, suggesting that the health burden may manifest as autoimmune or neurological pathology rather than just oncological outcomes (Monti et al., 2016).

### Animal Sentinel Outcomes (O2)

The animal data in Sardinia requires careful spatial interpretation to distinguish between mining legacies, military activities, and hunting practices.

**Wild Boar (*Sus scrofa*):** A key recent study by Mehmood et al. (2025) quantified lead concentrations in wild boar, finding mean liver concentrations of **6.70 mg/kg**, with maximums reaching much higher levels (Mehmood et al., 2025). It is vital to contextualise these findings geographically. The samples in this study originated largely from northern Sardinia, an area geologically distinct from the Sulcis mining district. The presence of lead in these animals, in the absence of mining or industrial smelting, implies the source is likely lead-based ammunition used in hunting. This highlights the wild boar as a sentinel for a *diffuse, behavioural* risk (lead ammunition in the food chain) rather than just a *geogenic* one.

**Marine Sentinels:** Bivalves in Sardinian coastal waters exhibit bioaccumulation of heavy metals (Cd, Pb) and PCBs, particularly in industrial and port areas (Piras et al., 2013). This mirrors the findings in Taranto but typically on a more localised scale depending on the specific bay or lagoon monitored.



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## Synthesised Data Tables

| Location | Primary Source / Citation | Outcome Type | Metric/Contaminant | Quantitative Result |
|---|---|---|---|---|
| Taranto | ISS Registry (Pirastu et al., 2014) | Epidemiological | SIR Liver Cancer (Men)<br>SIR Breast Cancer (Women) | +40%<br>+24% |
| | Giannico et al. (2024) | Epidemiological | HR Mortality (Breast Cancer) | HR 1.22 |
| | Mincuzzi et al. (2024) | Epidemiological | HR Mortality (Dementia Cohort) | HR 1.25 |
| | Vimercati et al. (2017) | Biomonitoring | Arsenic (As) & Chromium (Cr) | Elevated levels in urine |
| Campania | SENTIERI (Pirastu et al., 2011) | Epidemiological | SMR Larynx Cancer (Men)<br>SMR Bladder Cancer (Men) | SMR 115 (90% CI 105–127)<br>SMR 110.7 (90% CI 105–117) |
| | Perrone et al. (1999) | Biomonitoring | Lead (Pb) in Children's Blood | 60.0 ± 3.0 µg/L (urban) |
| | De Felip et al. (2014) | Biomonitoring | PCDD/F, PCBs (Breast Milk) | Significant accumulation detected |
| Sardegna | Cocco (2012) | Epidemiological | Hemolymphopoietic Cancer | Uncertain/No confirmed excess |
| | Monti et al. (2016) | Epidemiological | Multiple Sclerosis Prevalence | Positive association with heavy metals |
| | Varrica et al. (2014) | Biomonitoring | Lead (Pb) in Children's Hair | Significantly elevated near mines |

**Table** I. Summary of Selected Human Epidemiological and Biomonitoring Outcomes (O1). This table synthesises the verified human epidemiological data for the three case studies, highlighting statistically significant excesses in cancer incidence (SIR), mortality (SMR/HR), and direct biomonitoring evidence (blood, urine, hair, and breast milk).

| Location | Sentinel Species | Contaminant/Exposure | Key Quantitative Result | Citation |
|---|---|---|---|---|
| Taranto | *Mytilus galloprovincialis* | Dioxins (PCDD/F), PCBs, Heavy Metals (Cd, Pb, Cr) | Peak Dioxins: **14.88 pg WHO-TEQ/g** (EU Limit: 6.5)<br>Bioaccumulation confirmed | Giannico et al. (2022)<br>Lionetto et al. (2004) |
| | *Mullus barbatus* (Red Mullet) | Heavy Metals (Cr, Pb, Cd) | High Cr levels (**0.47–0.97 µg/g ww**) | Lionetto et al. (2004) |
| Campania | Livestock Products (Milk, Eggs) | Dioxins (PCDD/F), PCBs, Heavy Metals | Used to predict soil contamination<br>19 trace elements determined | Perugini et al. (2012)<br>Esposito et al. (2016) |
| | *Mytilus galloprovincialis* | PCBs | Extreme levels: **56.8 to 47,909.5 ng/g** | Naso et al. (2005) |
| Sardinia | *Sus scrofa* (Wild Boar) | Lead (Pb) | Liver mean: **6.70 mg/kg** (Max 34.87) | Mehmood et al. (2025) |
| | *Mytilus galloprovincialis* | Heavy Metals (Cd, Pb, Cr), PCBs | Bioaccumulation confirmed in transplanted and native samples | Piras et al. (2013) |

**Table** II. Summary of Selected Animal Sentinel Biomonitoring Outcomes (O2). The table aggregates representative quantitative contaminant levels (dioxins, PCBs, heavy metals) detected in sentinel species across the three SINs. Data points represent maximum or mean concentrations illustrating exceedances of regulatory limits (e.g., EU food safety limits) and confirming bioaccumulation in the food web. The column "Citation" provides the source of the specific quantitative values reported. Note: Table data aggregates representative findings from multiple sampling years to provide a consolidated view of contamination levels. Total study counts in the PRISMA diagram (43 O1, 33 O2) reflect the full evidentiary base.

# *Discussion: Interpreting the Sentinel Signal*

As summarised in Tables I and II, the quantitative synthesis of these findings validates the Sentinel Hypothesis, demonstrating that animal data frequently correlates with, and often precedes, human health outcomes in contaminated territories. In Taranto, the pathway is mechanistic: industrial emissions contaminate the marine environment, leading to bioaccumulation in mussels (O2) and subsequent human exposure (O1), manifesting as excess cancer risks. In Campania, the food chain link is evident, with PCBs in livestock products (O2) mirroring the lipophilic burden found in human breast milk (O1).



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## The "Systematic Delay" and Missed Warnings

This review highlights that veterinary data often precedes human diagnosis. In Taranto, the contamination of mussels and the subsequent destruction of livestock (e.g., the dioxin-related sheep slaughter in 2008) occurred years before the definitive SENTIERI mortality reports fully quantified the human toll (Conversano, 2014). In 2008, approximately 1,200 sheep were culled in the Taranto area after dioxin levels in their milk were found to exceed legal limits by vast margins. This veterinary intervention was a clear, loud signal of massive environmental bioavailability of carcinogens. Yet, the human epidemiological picture was only fully consolidated years later. Similarly, the widespread presence of lead in Sardinian wildlife and domestic animals has been a persistent signal of environmental bioavailability that predates and contextualises the findings of lead in children's hair. This lag confirms that the "systematic delay" is an administrative artifact, not a biological one; the data exists, but it is often siloed in veterinary inspectorates rather than integrated into public health risk models.

## Resolving the Sardinian Spatial Discrepancy: A Mosaic of Contamination

A key consideration for the Sardinia case study is the spatial distribution of sampling. The wild boar data from Mehmood et al. (2025) primarily sampled animals from northern Sardinia, a region not historically associated with the intense mining activities found in the Sulcis-Iglesiente (south-west Sardinia) or the military activities of Quirra (eastern Sardinia).

Rather than invalidating the sentinel hypothesis, this discrepancy reveals a **mosaic of contamination** affecting the island:

**1) The Mining Signal (south-western Sardinia):** In the Sulcis area, the correlation is spatially tight and geogenic/industrial. High environmental lead from mine tailings is reflected in both local livestock (O2) and, crucially, in the hair of local children (O1) (Varrica et al., 2014). Here, the sentinel and the human are exposed to the same soil/dust source.

**2) The Hunting/Ammunition Signal (Island-wide):** The finding of elevated lead in wild boars in the northern Sardinia (Mehmood et al., 2025), where mining is absent, points to a different source: lead-based ammunition. This serves as a distinct sentinel warning for "food safety" rather than "environmental pollution" per se. It alerts us that hunters and consumers of game meat across the entire island—not just in mining zones—are at risk of dietary lead exposure.

**3) The Military Signal (East):** In Quirra (PISQ), the epidemiological picture for O1 (cancer) remains uncertain. However, limited O2 data suggests heavy metal presence. The lack of a definitive human cancer cluster might imply that the health outcome being monitored (leukemia) is less sensitive than potential neurological or reproductive effects, or that the population size is too small for statistical power.

Therefore, the wild boar in Sardinia acts as a sentinel for a *diffuse* risk (lead ammunition) that overlays the *specific* risks of mining and military zones. This distinction is vital for public health interventions: remediation is needed in the SW, while behavioral change (switching to lead-free ammo) is needed island-wide.

## The Role of Official Controls and Compliance Monitoring

Scientific publications represent only the "tip of the iceberg" regarding available veterinary data. Local veterinary competent authorities (Italian Local Health Authorities, ASL) and the IZS network conduct rigorous, routine monitoring that constitutes a massive, unpublished sentinel system.

**Bivalve Monitoring:** In Sardinia and Taranto, ASL veterinarians conduct weekly or monthly sampling of shellfish harvesting areas (Classified Production Areas) to monitor for *E. coli* and marine biotoxins (e.g., PSP, DSP). This compliance data, though rarely published in academic journals, effectively prevents human outbreaks by triggering rapid harvesting bans when limits are exceeded.

**Piano Nazionale Residui (PNR):** The National Residue Control Plan is an annual surveillance programme coordinated by the Ministry of Health to monitor veterinary drugs and contaminants in food-producing animals. In 2024, thousands of samples were analysed for heavy metals and POPs. While the overall non-compliance rate is generally low, the detection of specific contaminants in organs like the liver or kidney provides a real-time map of environmental background levels that is currently under-utilised for human epidemiological forecasting.



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## Conclusions

This systematic review of 76 quantitative studies validates the "One Health Sentinel Hypothesis" as a robust, predictive tool for environmental health. The evidence demonstrates that animal sentinel data (O2)—whether it be dioxins in Taranto's mussels, PCBs in Campania's buffalo milk, or lead in Sardinia's wild boar—not only correlates with human health outcomes (O1) but often precedes them.

The animal sentinel is not merely a victim of pollution; it is a biological sensor. The correspondence between specific contaminant classes in animal tissues and specific pathologies in human populations confirms that veterinary surveillance is an underutilized asset in public health protection. The "systematic delay" observed in historical cases like Seveso and modern cases like Taranto is not a failure of the animals to signal danger, but a failure of human systems to interpret and act upon that signal.

To transition from reactive observation to proactive prevention, the following measures are recommended:

**1) Integration of Surveillance Systems:** The separation between veterinary (IZS/ASL) and human (ISS/Cancer Registries) databases must be bridged. A national "One Health" bio surveillance network should be established to mandate the cross-referencing of O2 contaminant data with O1 epidemiological signals.

**2) Operationalising the Sentinel:** Veterinary alerts (e.g., exceeding MRLs in milk or mussels) should automatically trigger human biomonitoring in the co-located population. If mussels in Taranto show high dioxin levels, the local population should be screened for body burden, reducing the "systematic delay" between environmental detection and public health intervention.

**3) Targeted Research in Sardinia:** Future studies in Sardinia should explicitly sample wild fauna *within* the PISQ military zone and the Sulcis mining areas simultaneously to differentiate between geogenic, military, and ammunition-derived contamination. This approach would resolve the spatial ambiguities identified in current literature and provide a clearer risk map for residents.

**4) Valorisation of Official Control Data:** Data from routine veterinary inspections (compliance monitoring) should be made accessible for epidemiological research. The "grey data" held by ASL and IZS represents a high-resolution temporal map of environmental toxicity that is currently under-utilised in academic and policy research.

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## Conflict 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.

## Ethical Statement

Not applicable. This article is a review of existing literature and does not involve any new studies with human participants or animals performed by the authors.

## Author Contributions

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