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Journal of Environmental & Earth Sciences

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REVIEW

Long-Term Environmental and Human Health Impacts of Hazardous Waste Incineration: A Case-Study in Catalonia, Spain

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ABSTRACT

This comprehensive review synthesizes findings from the studies conducted for more than two decades to assess environmental and human health impacts near Spain's first hazardous waste incinerator (HWI) located in Constantí (Tarragona, Catalonia). Through integrated analysis of polychlorinated dibenzo-p-dioxins/furans (PCDD/Fs) and metals across soil, vegetation, human tissues, and dietary matrices, the studies have shown: (1) PCDD/F concentrations decreased 75–96% in biological samples and dietary intake over 20 years, aligning with global emission reductions rather than HWI operations; (2) metal trajectories showed arsenic intermittently exceeding carcinogenic thresholds in soils (1.1×10^{-4} risk index) and chromium accumulating in autopsy tissues (+16% in kidney), although without HWI-specific spatial gradients; (3) systemic biomarkers revealed policy-driven declines—blood lead dropped 70% post-EU regulations, while mercury became undetectable in tissues post-2010. Health risk assessments confirmed that PCDD/F intake (0.122 pg WHO-TEQ/kg/day) remained still below WHO thresholds, with no attributable cancer risks for metals except legacy arsenic. The studies included in the program of surveillance show that PCDD/Fs and metals emissions by the HWI have meant a rather low contribution to population exposure to metals and PCDD/Fs compared to dietary and historical sources. However, residual risks warrant attention. It mainly concerns chromium speciation and arsenic in soils, as well as the effects on vulnerable subpopulations and the synergistic effects among toxicants. Epidemiological studies are also required.

Keywords: Hazardous Waste Incineration; Biomonitoring; Dioxins; Heavy Metals; Environmental Health; Risk Assessment

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ARTICLE INFO

Received: 27 March 2025 | Revised: 8 May 2025 | Accepted: 16 May 2025 | Published Online: 10 June 2025

DOI: https://doi.org/10.30564/jees.v7i6.9253

CITATION

Domingo, J.L., Rovira, J., Schuchmacher, M., 2025. Long-Term Environmental and Human Health Impacts of Hazardous Waste Incineration: A Case-Study in Catalonia, Spain. Journal of Environmental & Earth Sciences. 7(6): 227–243. DOI: https://doi.org/10.30564/jees.v7i6.9253

1. Introduction

Hazardous waste (HW) incineration is a process that burns HW at high temperatures to reduce volume, detoxify materials, and potentially recover energy. While HWI has been a widely adopted technology for managing HW, it poses significant risks to human health and the environment due to its dangerous properties, such as toxicity, corrosivity, or flammability [1]. Defined as waste capable of causing harm to ecosystems or human populations, HW originates from diverse industrial activities, including chemical manufacturing, mining, and petroleum processing. Globally, the HW generation has surged alongside industrialization. Among the waste generated in the EU in 2022, 119.0 million tons (5.3% of the total) were classified as HW [2]. While waste incineration offers advantages such as volume reduction, energy recovery, and detoxification, it remains a contentious disposal method due to its environmental and public health implications [3].

The primary environmental and health concerns associated with HW incinerators (HWIs) stem from the emission of toxic pollutants, mainly polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) and heavy metals. PCDD/Fs, first detected in municipal solid waste incinerator emissions in 1977 [4], are formed through complex processes including de novo synthesis, precursor synthesis, and chlorination, particularly in low-temperature zones of incineration systems. These persistent compounds, with long biological half-lives, are classified as group 1 carcinogens by the International Agency for Research on Cancer (IARC) [5] due to their association with cancer, infertility, and other adverse effects. Heavy metals, such as arsenic, cadmium, mercury, and lead, released primarily in ash, or as atmospheric particulates, also pose significant risks, including carcinogenicity, neurological disorders, and respiratory issues. Although HWIs constitute a smaller fraction of incineration facilities compared to municipal solid waste incinerators (MSWIs), their input materials—often highly variable and hazardous—amplify these risks, necessitating targeted research and monitoring.

Public opposition to HWIs is widespread, driven by fears of health impacts and historical associations with toxic emissions. This tension is exemplified in Catalonia, Spain, where the only HWI in the country was constructed in Constantí (Tarragona County) between 1996 and 1998, commencing operations in 1999. Prompted by significant local concern, a comprehensive monitoring program was initiated prior to its operation, assessing PCDD/Fs and metals in environmental, food, and biological samples, including blood, hair, breast milk, and autopsy tissues. That surveillance program, ongoing for over two decades, provided a unique opportunity to evaluate the long-term impacts of HWIs on both the environment and human health in a real-world setting.

Despite extensive research on MSWIs, data on HWIs remain limited, particularly regarding the influence of variable incineration materials and their specific health effects. In this sense, the Constantí HWI case offers critical insights into these gaps, addressing the need for evidence-based assessments of HW disposal technologies. The present review was aimed at synthesizing more than 20 years of monitoring data to evaluate the long-term environmental and human health impacts of that HWI, contributing to the broader discourse on sustainable waste management and public health protection.

2. Methodology

This review summarizes findings from studies conducted by the Laboratory of Toxicology and Environmental Health, Universitat Rovira i Virgili (Catalonia, Spain), spanning the period from 1996 to 2019. These studies, commissioned by the Waste Agency of the Generalitat de Catalunya, were designed to determine the environmental and human health impacts associated with emissions of metals and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) from the HWI located in Constantí. The review is structured into two primary sections: the first one shows a summary of research focused on PCDD/Fs, while the second one summarizes the research concerning metals.

Environmental samples (soil, vegetation) and biological samples (blood plasma, breast milk, adipose tissue) were analyzed for PCDD/Fs and metals using standardized methods. PCDD/F concentrations were generally determined using high-resolution gas chromatography coupled with mass spectrometry (HRGC/MS), while metals were mainly analyzed using inductively coupled plasma mass spectrometry (ICP-MS). These analytical methods remained consistent throughout the study period, with minor updates to align with evolving international standards (e.g., WHO-TEQ updates for PCDD/Fs). Dietary intake was assessed through analysis of food samples from local markets, with total intake estimated based on consumption patterns.

Medical records were not consulted to identify specific pollution-related health outcomes, as the study focused on biomarker-based exposure assessment rather than clinical epidemiology. On the other hand, air quality monitoring was not conducted as part of this study, although related studies assessed PCDD/F levels in ambient air in Catalonia, providing context for regional trends. Future studies incorporating air quality data and epidemiological analyses are recommended to complement the findings.

3. Summary of Studies on PCDD/Fs

3.1. Historical Context and Baseline Assessment of PCDD/Fs

The construction of Spain's first HWI in Constantí, prompted the implementation of an ambitious environmental monitoring program beginning in 1996, before the facility became operational. This baseline assessment phase was critical for establishing reference values against which future measurements could be compared to determine the potential impact of the facility on environmental PCDD/F levels and subsequent human exposure. Initial environmental sampling in 1996-1998 focused on soil and vegetation as primary environmental matrices for assessing PCDD/F contamination. Schuhmacher et al. [6] collected 40 soil samples within a 7 km radius of the yet-to-be-operational facility, with 30 representing rural areas and 10 representing urban settings. PCDD/F concentrations in these pre-operational samples ranged from 0.08 to 8.4 ng I-TEQ/kg dry matter in rural soils and 0.63 to 24.2 ng I-TEQ/kg dry matter in urban soils, with a mean value of 1.64 ng I-TEQ/kg across all samples. These baseline values were comparable to soil contamination levels reported in other countries, indicating that the area selected for the HWI had relatively low pre-existing PCDD/F contamination. Additionally, Schuhmacher et al. [7] analyzed 40 herbage samples from the same area, finding PCDD/F concentrations ranging between 0.24-1.22 ng I-TEQ/kg dry matter, with median and mean values of 0.53 and 0.61 ng I-TEQ/kg dry matter, respectively. Principal Component Analysis (PCA) was applied to these data, producing a two-dimensional model explaining 67% of the variance and establishing characteristic baseline patterns of PCDD/F distribution in the area's vegetation.

Human biomonitoring also formed a crucial component of the baseline assessment. Thus, Schuhmacher et al. [8] determined PCDD/F levels in plasma samples from 20 non-occupationally exposed subjects living near the planned facility. The mean concentration was 27.0 pg I-TEQ/g lipid, with a range from 14.8 to 48.9 pg I-TEQ/g lipid. All samples exhibited higher PCDD than PCDF levels, with women showing slightly higher concentrations (27.7 pg I-TEQ/g lipid) than men (25.2 pg I-TEQ/g lipid), although this difference was not statistically significant. A significant correlation ($r = 0.565$, $p < 0.01$) was observed between subject age and PCDD/F plasma levels, a relationship consistently noted in subsequent monitoring campaigns. Breast milk provided another important biological matrix for assessing baseline human exposure. Schuhmacher et al. [9] analyzed pooled samples from 15 mothers living in two residential areas near the planned facility, finding PCDD/F concentrations ranging between 5.9 and 17.1 pg I-TEQ/g fat, with a mean value of 11.8 pg I-TEQ/g fat. Slight variations were observed between urban and industrial areas. However, the differences generally lacked statistical significance. Completing the baseline exposure assessment, Domingo et al. [10] conducted a comprehensive analysis of PCDD/F levels in food items from local markets and supermarkets. That survey revealed that while meat, fish, eggs, and oils showed PCDD/F concentrations similar to, or lower than those reported in other countries, milk, vegetables, and cereals exhibited comparatively higher levels. Total dietary PCDD/F intake for the local population was estimated at 210 pg I-TEQ/day, somewhat higher than values reported in other countries at that time. This baseline dietary assessment would prove to be particularly valuable for interpreting subsequent trends in human biomarkers. Together, these pre-operational studies established a comprehensive baseline against which future measurements could be compared, representing one of the most thorough pre-operational assessments ever conducted for an HWI.

3.2. Environmental Monitoring Trends after HWI Operations

Following the commencement of operations at the Constantí HWI in 1999, the environmental monitoring program continued with regular sampling of soil and vegetation to detect potential changes in PCDD/F contamination patterns that might be attributable to the facility's emissions.

3.2.1. Soil Monitoring Results

A soil sampling campaign was conducted in 1998, with samples collected at the same 40 locations sampled during the baseline assessment. Schuhmacher et al. [11] reported PCDD/F concentrations in these samples between 0.12 and 17.20 ng I-TEQ/kg dry matter, with median and mean values of 0.75 and 1.59 ng I-TEQ/kg dry matter, respectively. When compared to the baseline values from 1996 (median: 0.67 ng I-TEQ/kg; mean: 1.68 ng I-TEQ/kg), no significant changes were detected, suggesting stability in soil PCDD/F contamination. Long-term soil monitoring continued over subsequent years. In relation to it, Marquès et al. [12] summarized the results from the 2013-2016 monitoring period, reporting median PCDD/F concentrations in soils of 0.44 and 0.33 ng I-TEQ/kg in 2015 and 2016, respectively. These values represented a significant decrease compared to baseline measurements, along with a non-significant decreasing trend between 2015 and 2016. This long-term decline in soil PCDD/F concentrations during the operational period suggested that the HWI did not contribute to increase soil contamination in surrounding areas. In fact, the data indicated a general reduction in environmental PCDD/F levels over the monitoring period, consistent with broader regional and global trends resulting from various regulatory and technological improvements aimed at reducing PCDD/F emissions from all sources.

3.2.2. Vegetation Monitoring Results

Vegetation sampling continued in parallel with soil monitoring to assess potential atmospheric deposition of PCDD/Fs. Schuhmacher et al. [13] analyzed herbage samples collected in April 2000, approximately 20 months after the HWI began operating, at the same sampling points used in previous surveys. PCDD/F concentrations ranged between 0.13 and 0.65 ng I-TEQ/kg dry matter, with median and mean values of 0.29 and 0.32 ng I-TEQ/kg dry matter, respectively. Comparing these results with the 1996 baseline (median: 0.53 ng I-TEQ/kg; mean: 0.61 ng I-TEQ/kg) revealed a significant decrease (49%, $p < 0.001$) in mean PCDD/F levels during the pre-operational period from 1996-1998, followed by a statistically non-significant increase of 3% ($p > 0.05$) from 1998-2000, after the HWI began regular operations. The slight increase observed after facility commissioning prompted two potential hypotheses: either PCDD/F emissions from the HWI were not entirely negligible, or emissions from other sources in the area remained at similar levels to those reached in 1998. Nevertheless, exhaustive evaluation of the data indicated an absence of notable PCDD/F contamination attributable to the HWI in its area of influence. Long-term vegetation monitoring between 2013 and 2016, as reported by Marquès et al. [12], showed some fluctuations in PCDD/F levels. Concentrations in 2013 (1.11 ng I-TEQ/kg) were similar to those found in 2012 (1.23 ng I-TEQ/kg) but then decreased substantially in subsequent years (0.16, 0.23, and 0.17 ng I-TEQ/kg in 2014, 2015, and 2016, respectively). These fluctuations were attributed more to environmental factors than to variations in PCDD/F emissions from the HWI.

A particularly rigorous assessment conducted by Ferré-Huguet et al. [14], four years after the start of regular operations, compared PCDD/F congener profiles in environmental samples, collected before and after the HWI was operating, as well as profiles from the facility's air emissions. The environmental monitoring data from both soil and vegetation suggested that the operation of the HWI did not result in increased PCDD/F contamination in the surrounding environment. The general decreasing trend observed in environmental matrices over the monitoring period, aligned with broader temporal patterns of declining PCDD/F levels resulting from improvements in various industrial sectors and environmental regulations.

3.3. Human Biomonitoring Outcomes

Human biomonitoring provides the most direct evidence of actual human exposure to environmental contaminants. The monitoring program around the Constantí HWI included three different biological matrices—blood plasma, adipose tissue, and breast milk—each offering unique advantages for assessing PCDD/F exposure patterns and trends.

3.3.1. Plasma PCDD/F Levels

Following the baseline assessment of plasma PCDD/F levels (mean: 27.0 pg I-TEQ/g lipid) prior to HWI operations, approximately three years after the facility began regular operations, Agramunt et al. [15] conducted follow-up monitoring. That study found a mean PCDD/F concentration of 15.70 pg I-TEQ/g lipid (range: 4.66-29.25 pg I-TEQ/g lipid), significantly lower than the baseline value. Reductions were observed across both sexes and all age groups, suggesting a population-wide decrease in exposure. This decreasing trend continued in subsequent monitoring campaigns. Thus, Nadal et al. [16] reported a mean plasma PCDD/F concentration of 9.36 pg I-TEQ/g lipid (range: 1.76-23.44 pg I-TEQ/g lipid) in 2007, representing a further significant reduction compared to both baseline and 2002 levels. It was noted that this decrease aligned with concurrent reductions in dietary PCDD/F intake for the same population, which had fallen from 210.1 pg I-TEQ/day in 1998 to 63.8 pg WHO-TEQ/day in 2002 and further to 27.8 pg WHO-TEQ/day in 2007 (see below data). Further monitoring by Nadal et al. [17] found a mean plasma PCDD/F concentration of 6.18 pg I-TEQ/g lipid (range: 2.03-18.8 pg I-TEQ/g lipid), representing a 77% reduction from baseline levels ($p < 0.001$). A physiologically-based pharmacokinetic (PBPK) model was employed to estimate theoretical plasma PCDD/F concentrations based on dietary intake data, yielding values (7.95 pg I-TEQ/g lipid) very similar to those measured experimentally (6.18 pg I-TEQ/g lipid). This close agreement between modeled and measured values further supported the conclusion that dietary intake, rather than local environmental exposure, was the primary determinant of plasma PCDD/F levels. The most recent plasma monitoring conducted by Nadal et al. [18] reported a mean PCDD/F concentration of 6.79 pg I-TEQ/g lipid, significantly lower than the baseline value, and comparable to the 2012 level (6.18 pg I-TEQ/g lipid). The authors emphasized that this substantial reduction in plasma PCDD/F levels corresponded with the decreasing trend in dietary PCDD/F intake, which had fallen from 210.1 pg I-TEQ/day at baseline, to 8.54 pg WHO-TEQ/day in that survey. The consistent decreasing trend in plasma PCDD/F concentrations over the two-decade monitoring period, paralleling reductions in dietary intake, provided evidence that the HWI was not increasing PCDD/F exposure for the local population.

3.3.2. Adipose Tissue

Adipose tissue represents an important storage compartment for lipophilic compounds like PCDD/Fs and provides valuable information about long-term cumulative exposure. In a baseline study, PCDD/F levels were analyzed in the adipose tissue of 15 autopsied individuals from Tarragona, Spain, who had lived there for at least 10 years (Schuhmacher et al., [19]). Concentrations ranged from 13.37 to 69.37 ng I-TEQ/kg fat (mean and median values of 30.98 and 26.30 ng I-TEQ/kg fat), with higher levels in women than men. Residents in industrial areas had slightly elevated levels, although not statistically significant. The detected PCDD/F levels were comparable to those in other industrialized nations. A few years later, Schuhmacher et al. [20] analyzed adipose tissue samples from 15 autopsied subjects, who had been living in the area potentially affected by the HWI, approximately three years after the facility began operations. PCDD/F concentrations ranged between 1.5 and 41 pg WHO-TEQ/g fat, with a mean value of 11 pg WHO-TEQ/g fat. This represented a substantial reduction from the baseline mean of 31 pg I-TEQ/g fat, consistent with decreases observed in plasma and dietary intake. Subsequent monitoring by Nadal et al. [21], after approximately nine years of HWI operations, found a mean PCDD/F concentration in adipose tissue of 14.6 pg WHO-TEQ/g fat (range: 3.3-55.4 pg WHO-TEQ/g fat). This represented an increase compared to the 2002 levels, despite continuing decreases in plasma levels and dietary intake during the same period. The authors noted that women showed higher levels than men (23.8 vs. 11.2 pg WHO-TEQ/g fat) and suggested that the increase would not be directly attributable to exposure from HWI emissions, particularly given that other biomarkers such as plasma and milk showed decreasing trends during the same period.

Further monitoring by Schuhmacher et al. [22] found mean and median PCDD/F concentrations of 11.5 and 7.4 pg WHO-TEQ/g fat, respectively, significantly lower (64%) than baseline values but not significantly different from 2002 levels. The authors again observed an increase in adipose tissue PCDD/F concentrations with age, while there were no significant differences according to gender. A PBPK model applied to estimate adipose tissue PCDD/F levels yielded results very similar to measured values across all four survey periods, validating this approach for predicting internal PCDD/F doses. The most recent adipose tissue monitoring was conducted by García et al. [23], who found a mean PCDD/F concentration of 6.63 pg WHO-TEQ/g fat in 2019, ranging from 0.95 to 12.95 pg WHO-TEQ/g fat. This represented a significant reduction from the baseline value and was substantially lower than levels observed in all previous surveys. The authors confirmed a strong correlation between PCDD/F body burden and age and noted that the significant reduction in adipose tissue PCDD/F levels aligned with the decreasing trend in dietary intake (from 210.1 pg I-TEQ/day in 1998 to 8.54 pg WHO-TEQ/day in 2018). The fluctuations observed in adipose tissue PCDD/F levels across surveys, particularly the increase in 2007, suggested that factors other than current exposure—such as mobilization from fat stores during weight loss, variations in the study population, or age-related bioaccumulation—might influence adipose tissue levels at specific time points. However, the overall trend across the two-decade monitoring period shows a substantial reduction in adipose tissue PCDD/F concentrations, consistent with decreases in dietary exposure.

3.3.3. Breast Milk Monitoring Results

Breast milk provides a non-invasive matrix for assessing maternal body burden of persistent organic pollutants and evaluating potential exposure to nursing infants. Following the baseline assessment of breast milk PCDD/F levels (mean: 11.8 pg I-TEQ/g fat) [9], Schuhmacher et al. [24] conducted follow-up monitoring after three years of HWI operations. PCDD/F concentrations ranged from 4.9 to 39.9 pg I-TEQ/g fat, with a median value of 7.7 pg I-TEQ/g fat, representing a notable reduction from baseline levels. The authors attributed this decrease to the contemporaneous reduction in dietary PCDD/F intake and concluded that living near the HWI did not pose additional health risks from PCDD/F exposure. Further monitoring by Schuhmacher et al. [25] found continued decreases in breast milk PCDD/F levels, with concentrations ranging from 45 to 143 pg/g fat (2.8 to 11.2 pg WHO-TEQ/g fat). Interestingly, PCDD/F levels in milk from women living in urban areas were higher than those from industrial zones, contrary to what might be expected if the HWI were a significant exposure source. This pattern persisted in subsequent monitoring by Schuhmacher et al. [26], who reported total concentrations of PCDD/Fs in breast milk ranging from 18 to 126 pg/g fat (1.1-12.3 pg WHO-TEQ/g fat). Again, levels were higher in milk from women in urban zones compared to industrial zones, and an overall decrease in PCDD/F concentrations was observed. The most recent breast milk monitoring reported by Schuhmacher et al. [27] found a mean PCDD/F concentration of 2.26 pg WHO-TEQ/g fat, with no significant differences between women living in industrial and urban areas (1.67 pg vs. 2.48 pg WHO-TEQ/g fat). This represented a very remarkable reduction compared to baseline levels. The authors concluded that the profiles of PCDD/Fs in breast milk were similar regardless of residential area and collection period, being primarily influenced by dietary factors such as intake of fish, meat, oils, and fats rather than by proximity to the HWI. The consistent decreasing trend in breast milk PCDD/F concentrations over the two-decade monitoring period, paralleling reductions in dietary intake and showing higher levels in urban than industrial areas, provided compelling evidence that the HWI did not increase PCDD/F exposure for the local population.

3.4. Dietary Exposure Assessment and Trends

Diet represents the primary exposure pathway for PCDD/Fs in the general population. The monitoring program around the Constantí HWI included comprehensive dietary exposure assessment through periodic analysis of food samples and estimation of total dietary intake, providing crucial context for interpreting the human biomonitoring results.

The baseline dietary survey conducted by Domingo et al. [10] established an initial dietary PCDD/F intake of 210 pg I-TEQ/day for the Tarragona population. This value was higher than dietary intakes reported for many other countries at that time, partly due to the inclusion of food groups often excluded from such calculations, such as vegetables, fruits, and cereals, which made substantial contributions to the total in this Mediterranean population.

A follow-up dietary assessment by Bocio and Domingo [28] analyzed 36 composite food samples collected in 2002, finding a total dietary PCDD/F intake of 59.6 pg I-TEQ/day (63.8 pg WHO-TEQ/day). This represented a dramatic reduction from the baseline value in just four years. Fish and seafood (33.7%), oils and fats (15.3%), cereals (14.4%), and dairy products (13.7%) were identified as the primary contributors to this intake. Further monitoring by Martí-Cid et al. [29], based on food samples collected in 2006, estimated a total dietary PCDD/F intake of 27.81 pg WHO-TEQ/day, less than half the 2002 value, and approximately 87% lower than the baseline intake. Fish and seafood (28%), oils and fats (22%), eggs (17%), and dairy products (11%) were the major contributors, while pulses (1%), milk (2%), vegetables (3%), and fruits (3%) made the lowest contributions. Domingo et al. [30] conducted another dietary assessment based on samples collected in 2010, estimating a total intake of 33.1 pg WHO-TEQ/day. This represented a slight increase from the 2006 value but remained substantially lower than both baseline and 2002 intakes. Fish and seafood, oils and fats, dairy products, and industrial bakery products were identified as the food groups making the largest contributions to total intake.

The most recent dietary assessment reported by González et al. [31] found a total PCDD/F intake of 8.54 pg WHO-TEQ/day for the adult population, with fish and seafood making the greatest contribution, followed by eggs, meat, and oils and fats. This represented a considerable reduction from the 2010 value, and an astonishing 96% reduction from the baseline intake established two decades earlier. That reduction was characterized as “spectacular”, being that intake (0.122 pg WHO-TEQ/kg body weight) was lower than most reported values from other regions and countries. The progressive and substantial reduction in dietary PCDD/F intake observed over the two-decade monitoring period was consistent with broader regional and global trends resulting from various regulatory and technological improvements aimed at reducing environmental PCDD/F contamination from all sources. This dramatic decrease in dietary exposure provided a compelling explanation for the parallel reductions observed in human biomarkers, supporting the conclusion that changes in food contamination, rather than local industrial emissions including those from the HWI, were the primary determinant of human PCDD/F body burden in the population living near the facility.

3.5. Health Risk Assessment and Public Health Implications

A central objective of the monitoring program was to assess potential health risks associated with PCDD/F exposure for the population living near the HWI. Several studies specifically addressed this question through formal risk assessment methodologies. Thus, Ferré-Huguet et al. [14] conducted a comprehensive assessment four years after the start of regular HWI operations, evaluating both carcinogenic and non-carcinogenic risks for adults and children living in the vicinity of the facility. Their analysis, which included comparison of PCDD/F congener profiles in environmental samples before and after HWI was operating, as well as profiles from stack emissions, concluded that the facility "does not cause additional risks to the environment or to the population living in the vicinity of the facility". Similarly, Marquès et al. [12] evaluated health risks based on environmental PCDD/F concentrations measured between 2013 and 2016, concluding that "exposure to PCDD/Fs in the area under potential influence of the HWI was not of concern, as the current environmental concentrations of PCDD/Fs did not mean additional carcinogenic or non-carcinogenic risks for the local population".

These formal risk assessments were supported by several lines of evidence from the monitoring program: Firstly, the dietary intake of PCDD/Fs for the population near the HWI (0.122 pg WHO-TEQ/kg body weight/day as of 2018) was well below the tolerable daily intake range of 1-4 pg TEQ/kg body weight/day established by the World Health Organization, indicating that even for individuals with high consumption of the most contaminated food groups, dietary exposure to PCDD/Fs did not exceed levels considered safe for lifetime exposure. Secondly, the recent levels of PCDD/Fs in human biological matrices (plasma, adipose tissue, and breast milk) were generally lower than those reported in studies from other regions, suggesting that the population living near the HWI was not subject to elevated exposure compared to other populations. Thirdly, the most significant reduction in PCDD/F levels across all matrices occurred between the baseline and the first follow-up surveys, coinciding with the start of HWI operations. If the facility were a significant source of PCDD/Fs, an increase rather than a decrease would be expected following regular operations. Fourth, in several surveys, PCDD/F levels in human biological matrices were higher in urban areas compared to industrial areas closer to the HWI, contrary to what would be expected if the facility were a major source. Finally, the decrease in human body burden of PCDD/Fs closely paralleled the decrease in dietary intake, suggesting that changes in food contamination, rather than local industrial emissions, were the primary driver of reduced exposure.

In general, these findings collectively indicate that the operation of the HWI has not resulted in increased PCDD/F exposure or associated health risks for the local population. However, it is important to note that the monitoring program focused specifically on PCDD/Fs (and metals: see next sections) and did not address all potential contaminants of concern from the facility. Studies have not included those chemicals that are not routinely analyzed, even some of them probably unknown right now. Furthermore, potential interactions among multiple chemicals were not considered in the risk assessments.

From a public health perspective, the findings from this monitoring program are reassuring, indicating that properly designed, operated, and regulated hazardous waste incineration facilities not necessarily pose significant PCDD/F-related health risks to nearby populations. However, comprehensive epidemiological studies directly assessing health outcomes in populations near waste incinerators would provide more definitive evidence regarding potential health impacts beyond what can be determined from exposure assessment alone.

Table 1 provides a comprehensive summary of the key findings and methodological parameters from the PCDD/F studies discussed above.

Table 1. Summary of Studies on PCDD/Fs Near the Hazardous Waste Incinerator in Constantí, Catalonia, Spain.

Sampling Period	Matrix	Mean/Median (Units)	Highlights/Remarks	Reference
1996	Soil	Range: 0.08-8.4 ng I-TEQ[1]^a/kg (rural); 0.63-24.2 ng I-TEQ/kg (urban); Mean: 1.64 ng I-TEQ/kg	Baseline assessment before HWI operation; values comparable to other countries; samples taken within a 7 km radius of the planned facility.	Schuhmacher et al. [6]
1996	Herbage	Range: 0.24-1.22 ng I-TEQ/kg; Median: 0.53 ng I-TEQ/kg; Mean: 0.61 ng I-TEQ/kg	Baseline assessment; characteristic patterns established using Principal Component Analysis; 40 samples collected.	Schuhmacher et al. [7]
1996-1998	Blood Plasma	Range: 14.8-48.9 pg I-TEQ/g lipid; Mean: 27.0 pg I-TEQ/g lipid	Baseline assessment; significant positive correlation with age ($r=0.565$, $p<0.01$); women slightly higher than men (not statistically significant); 20 non-occupationally exposed subjects.	Schuhmacher et al. [8]
1996-1998	Breast Milk	Range: 5.9-17.1 pg I-TEQ/g fat; Mean: 11.8 pg I-TEQ/g fat	Baseline assessment; slight variations between urban and industrial areas (not statistically significant); pooled samples from 15 mothers.	Schuhmacher et al. [9]
1996-1998	Adipose Tissue	Range: 13.37-69.37 ng I-TEQ/kg fat; Mean: 30.98 ng I-TEQ/kg fat; Median: 26.30 ng I-TEQ/kg fat	Baseline assessment; higher levels in women than men; residents in industrial areas had slightly elevated levels (not statistically significant); 15 autopsied individuals who had lived in the area for at least 10 years.	Schuhmacher et al. [19]
1998	Food Items	Mean: 210 pg I-TEQ/day (total dietary intake)	Baseline assessment; higher values than other countries; milk, vegetables, and cereals exhibited comparatively higher levels.	Domingo et al. [10]
1998	Soil	Range: 0.12-17.20 ng I-TEQ/kg; Median: 0.75 ng I-TEQ/kg; Mean: 1.59 ng I-TEQ/kg	No significant changes were detected from the 1996 baseline; samples were collected at the same 40 locations.	Schuhmacher et al. [11]
2000	Herbage	Range: 0.13-0.65 ng I-TEQ/kg; Median: 0.29 ng I-TEQ/kg; Mean: 0.32 ng I-TEQ/kg	49% decrease from 1996 baseline ($p<0.001$), followed by a non-significant 3% increase from 1998-2000 after HWI operations began; no notable contamination attributable to HWI.	Schuhmacher et al. [13]

Table 1. *Cont.*

Sampling Period	Matrix	Mean/Median (Units)	Highlights/Remarks	Reference
2002	Food Items	Mean: 63.8 pg WHO-TEQ^b/ day (total dietary intake)	Dramatic reduction from baseline; major contributors: fish/seafood (33.7%), oils/fats (15.3%), cereals (14.4%), dairy products (13.7%); 36 composite food samples analyzed.	Bocio and Domingo [28]
2002	Blood Plasma	Range: 4.66-29.25 pg I-TEQ/g lipid; Mean: 15.70 pg I-TEQ/g lipid	Significant reduction from baseline across all age groups and sexes; approximately three years after HWI began regular operations.	Agramunt et al. [15]
2002	Adipose Tissue	Range: 1.5-41 pg WHO-TEQ/g fat; Mean: 11 pg WHO-TEQ/g fat	Substantial reduction from baseline mean (31 pg I-TEQ/g fat); approximately three years after HWI began operations; 15 autopsied subjects.	Schuhmacher et al. [20]
2002	Breast Milk	Range: 4.9-39.9 pg I-TEQ/g fat; Median: 7.7 pg I-TEQ/g fat	Notable reduction from baseline levels; decrease attributed to reduction in dietary PCDD/F intake.	Schuhmacher et al. [24]
2006	Food Items	Mean: 27.81 pg WHO-TEQ/day (total dietary intake)	87% lower than baseline; less than half the 2002 value; major contributors: fish/seafood (28%), oils/fats (22%), eggs (17%), dairy products (11%).	Martí-Cid et al. [29]
2007	Blood Plasma	Range: 1.76-23.44 pg I-TEQ/g lipid; Mean: 9.36 pg I-TEQ/g lipid	Further significant reduction; aligned with decreases in dietary PCDD/F intake.	Nadal et al. [16]
2007	Adipose Tissue	Range: 3.3-55.4 pg WHO-TEQ/g fat; Mean: 14.6 pg WHO-TEQ/g fat	Increase compared to 2002 levels despite decreasing plasma levels and dietary intake; women showed higher levels than men (23.8 vs. 11.2 pg WHO-TEQ/g fat).	Nadal et al. [21]
2007	Breast Milk	Range: 2.8-11.2 pg WHO-TEQ/g fat (45-143 pg/g fat total)	PCDD/F levels the higher in milk from women living in urban areas than in industrial zones (contrary to the expected pattern if HWI were a significant source).	Schuhmacher et al. [25]
2010	Food Items	Mean: 33.1 pg WHO-TEQ/day (total dietary intake)	Slight increase from 2006 value but substantially lower than baseline; major contributors: fish/seafood, oils/fats, dairy products, industrial bakery products.	Domingo et al. [30]
2012	Blood Plasma	Range: 2.03-18.8 pg I-TEQ/g lipid; Mean: 6.18 pg I-TEQ/g lipid	77% reduction from baseline ($p<0.001$); close agreement between measured values and PBPK model estimates (7.95 pg I-TEQ/g lipid).	Nadal et al. [17]
2012	Breast Milk	Range: 1.1-12.3 pg WHO-TEQ/g fat (18-126 pg/g fat total)	Overall decrease from previous surveys; higher levels in urban zones than industrial zones; profiles similar regardless of residential area.	Schuhmacher et al. [26]
2012	Adipose Tissue	Range: N/A; Median: 7.4 pg WHO-TEQ/g fat; Mean: 11.5 pg WHO-TEQ/g fat	64% lower than baseline; not significantly different from 2002 levels; PBPK model validation showed close agreement with measured values.	Schuhmacher et al. [22]
2013-2016	Vegetation	Range: N/A; 1.11 ng I-TEQ/kg (2013); 0.16 ng I-TEQ/kg (2014); 0.23 ng I-TEQ/kg (2015); 0.17 ng I-TEQ/kg (2016)	Substantial decrease after 2013; fluctuations attributed to environmental factors rather than variations in HWI emissions.	Marquès et al. [12]
2015-2016	Soil	Range: N/A; Median: 0.44 ng I-TEQ/kg (2015); 0.33 ng I-TEQ/kg (2016)	Significant decrease compared to baseline measurements; non-significant decreasing trend between 2015 and 2016.	Marquès et al. [12]
2018	Food Items	Mean: 8.54 pg WHO-TEQ/day (total intake); 0.122 pg WHO-TEQ/kg body weight/day	"Spectacular" 96% reduction from baseline; lower than most reported values from other regions; fish/seafood, eggs, meat, and oils/fats were the main contributors.	González et al. [31]
2018	Blood Plasma	Range: N/A; Mean: 6.79 pg I-TEQ/g lipid	Significantly lower than baseline value; comparable to 2012 level; substantial reduction corresponding with decreasing trend in dietary intake.	Nadal et al. [18]

Table 1. *Cont.*

Sampling Period	Matrix	Mean/Median (Units)	Highlights/Remarks	Reference
2018	Breast Milk	Range: N/A; Mean: 2.26 pg WHO-TEQ/g fat	No significant differences between women living in industrial and urban areas; a very remarkable reduction compared to baseline levels.	Schuhmacher et al. [27]
2019	Adipose Tissue	Range: 0.95-12.95 pg WHO-TEQ/g fat; Mean: 6.63 pg WHO-TEQ/g fat	Significant reduction from baseline and substantially lower than previous surveys; strong correlation between PCDD/F body burden and age; aligned with decreasing trend in dietary intake.	García et al. [23]

[1] I-TEQ: International Toxic Equivalents (NATO/CCMS, 1988). This is an older TEQ scheme. WHO-TEQ: World Health Organization Toxic Equivalents.

4. Summary of Studies on Metals

4.1. Soils and Herbage

Llobet et al. [32] conducted a study aimed to determine baseline levels of metals in soil and herbage before the HWI began operations. In 1996 and 1998, 40 soil and 40 herbage samples were collected at distances of 250 to 4000 meters from the HWI, analyzing the concentrations of As, Be, Cd, Cr, Hg, Mn, Ni, Pb, Sn, Tl, and V. Results were analyzed by wind direction and distance, providing baseline data for future impact assessments. That study was crucial as it set the initial conditions before the HWI started operating. Nadal et al. [33] revisited the same sampling points in 2003, after the HWI had been operational. Increases in As, Be, Cr, Ni, and V in soils were found, but decreases were noted in Cd, Hg, and Sn levels. In herbage, Cr, Mn, and V increased, while As decreased. Human health risk assessments indicated that noncarcinogenic risks were within safe limits, but As exceeded carcinogenic risk limits, suggesting a potential concern. Similarly, Ferré-Huguet et al. [34] continued monitoring (in the period 2004-2005), detecting Hg in only four soil samples, with Mn being the most abundant metal in soils. In herbage, as was detected only in samples far from the HWI, and Be, Cr, and Tl were below detection limits. Metal levels were generally low, comparable to other industrial areas, with no significant health risks identified, reinforcing the minimal impact of the HWI. On the other hand, in 2011 Vilavert et al. [35] measured metal concentrations in 30 soil samples, with Mn being again the most abundant (316.4 µg/g). From 1998 to 2011, As, Cr, Sn, Tl, and V showed significant increases, but health risk assessments indicated no significant carcinogenic or noncarcinogenic risks, suggesting the HWI's impact was being limited.

4.2. Metals in Blood

Llobet et al. [36] collected blood samples from 72 men and 72 women living near the HWI under construction, and the levels of As, Be, Cd, Cr, Hg, Mn, Ni, Pb, Sn, Tl, and V were analyzed. As, Be, Tl, V were below detection limits, with Cd at 0.70 µg/dL and Pb at 3.83 µg/dL. The study provided baseline data essential for future comparisons. In 2007, Ferré-Huguet et al. [37] analyzed blood samples from 144 adults, with Be, Hg, Mn, Sn, Tl below detection limits, and Cd at 0.34 µg/dL, and Pb at 2.40 µg/dL. There was stability or reduction compared to 1998 and 2002, suggesting no adverse impact from the HWI. Similarly, Esplugas et al. [38] conducted sampling in 2012 and 2017, with Pb at 21.7 µg/kg in 2012, and Cu at 931 µg/kg in 2017. Compared to 1998, Hg, Mn, Pb levels decreased, with no additional health risk from HWI emissions, aligning with international reference values.

4.3. Metals in Hair

In a baseline study, Granero et al. [39] analyzed hair from 124 schoolchildren (aged 11-13 years), with Be, Tl, V below detection limits, and Pb ranging from 0.38 to 23.83 µg/g. No significant sex differences, but variations by residence area for As, Cd, Cr, Hg, Sn were found, providing essential baseline data for future assessments. In 2003, Nadal et al. [40] analyzed hair from 134 schoolchildren, with Hg at 0.70 µg/g and Pb at 0.86 µg/g, showing reductions in Cr, Mn, Ni, Pb, Sn compared to 1996-1998, with no significant sex differences and minimal HWI impact. More recently, Esplugas et al. [41] found levels of metals following this order: Pb > Hg > Ni > Sn > Mn > Cr, with As, Be, Tl not detected, while Cr, Pb levels decreased compared to 1998, with concentrations similar to other contaminated areas, confirming minimal HWI influence.

4.4. Metals in Autopsy Tissues

Autopsy tissue studies provide long-term exposure data, assessing metal accumulation. Llobet et al. [42] analyzed tissues from 20 subjects before HWI operation, with Be, Tl, V below detection limits, and highest levels of Cd, Hg in kidney, Mn in liver, and As, Cr, Ni, Pb, Sn, Zn in bone, higher in males, establishing baseline levels. In 2003, Bocio et al. [43] collected autopsy samples from 22 individuals. As, Be, Tl, V were not detected, but Cd and Hg levels were high in the kidney, and Mn in the liver. There were reductions compared to baseline levels, suggesting no increased exposure from HWI. Similarly, Mari et al. [44] collected tissue samples of 20 subjects, which showed Cd highest in kidney (21.15 µg/g) and Pb in bone (1.39 µg/g), with As, Be, Ni, Tl, V below detection. The results were, in general, comparable to general populations, reinforcing minimal HWI impact. More recently (2019), García et al. [45] collected tissue samples of 20 individuals. Sample showed As, Be, Tl, V not detected, with Cr increasing and Pb decreasing over time, with no evidence of increased health risks, confirming long-term safety for the monitored population.

4.5. Dietary Exposure to Metals

Llobet et al. [46] carried out a baseline study in which various food items were analyzed, with Be, Tl, V below the limit of detection, and daily intakes like of As at 272.7 µg, and Pb at 48.6 µg, posing no health hazard. In 2003, Bocio et al. [43] collected foods to be analyzed for metal concentrations. The analysis showed Be, Tl below the limits of detection, with As at 458.5 µ g/day, below PTWI for toxic elements, similar to baseline, indicating safe dietary exposure. Similarly, in 2006, foodstuffs showed Be, Tl, V below detection, with As at 351 µ g/day, Pb at 39.9 µ g/day. Fish and seafood were the main contributors, and the dietary intake was below PTWI, confirming safety [47].

The critical data points and outcomes extracted from the aforementioned studies are summarized in **Table 2**.

Table 2. Summary of Studies on Metals Near the Hazardous Waste Incinerator in Constantí, Catalonia, Spain.

Sampling Period	Matrix	Mean/Median (Units)	Highlights/Remarks	Reference
1996-1998	Soil and herbage	N/A (Specific values not provided for all metals in the text)	Baseline assessment before HWI operation; analysis of As, Be, Cd, Cr, Hg, Mn, Ni, Pb, Sn, Tl, V; samples collected at distances of 250 to 4000 meters from planned HWI.	Llobet et al. [32]
1998	Blood	As, Be, Tl, V: Below detection limit; Cd: 0.70 µg/dL; Pb: 3.83 µg/dL	Baseline assessment from 72 men and 72 women living near HWI under construction.	Llobet et al. [36]
1998	Autopsy tissues	Be, Tl, V: Below detection limit; Highest levels of Cd, Hg in kidney; Mn in liver; As, Cr, Ni, Pb, Sn, Zn in bone	Baseline assessment; showed higher levels in males; 20 subjects examined.	Llobet et al. [42]
1998	Food items	Be, Tl, V: Below detection limit; As: 272.7 µ g/day ; Pb: 48.6 µ g/day	Baseline dietary assessment; showed no health hazard from metal intake.	Llobet et al. [46]
1998	Hair	Be, Tl, V: Below detection limit; Pb: Range 0.38-23.83 µg/g	Baseline assessment of 124 schoolchildren (aged 11-13 years); no significant sex differences; variations by residence area for As, Cd, Cr, Hg, Sn.	Granero et al. [39]
2003	Soil and herbage	N/A (Specific values not provided for all metals in the text. Increases/decreases are relative.)	Four years after HWI operations began; increases in As, Be, Cr, Ni, V in soils; decreases in Cd, Hg, Sn in soils; increases in Cr, Mn, V in herbage; decrease in As in herbage; noncarcinogenic risks within safe limits; As exceeded carcinogenic risk limits.	Nadal et al. [33]
2003	Hair	Hg: 0.70 µg/g; Pb: 0.86 µg/g	Reductions in Cr, Mn, Ni, Pb, Sn compared to baseline; no significant sex differences; 134 schoolchildren examined.	Nadal et al. [40]
2003	Autopsy tissues	As, Be, Tl, V: Not detected; High Cd, Hg in kidney; High Mn in liver	Reductions compared to baseline levels; 22 individuals examined.	Bocio et al. [43]
2003	Food items	Be, Tl: Below detection limit; As: 458.5 µ g/day	Below PTWI (Provisional Tolerable Weekly Intake) for toxic elements; similar to baseline dietary exposure.	Bocio et al. [43]

Table 2. *Cont.*

Sampling Period	Matrix	Mean/Median (Units)	Highlights/Remarks	Reference
2004-2005	Soil and herbage	N/A (Specific values not provided for all metals)	As detected only in samples far from HWI; Be, Cr, Tl below detection limits in herbage; metal levels generally low, comparable to other industrial areas; no significant health risks identified.	Ferré-Huguet et al. [34]
2006	Food items	Be, Tl, V: Below detection; As: 351 μ g/day ; Pb: 39.9 μ g/day	Fish and seafood were the main contributors; dietary intake was below PTWI, confirming safety.	Martí-Cid et al. [47]
2007	Blood	Be, Hg, Mn, Sn, Tl: Below detection; Cd: 0.34 μg/dL; Pb: 2.40 μg/dL	Stability or reduction compared to 1998 and 2002; 144 adults examined; no adverse impact from HWI.	Ferré-Huguet et al. [37]
2009-2010	Soil	N/A (Specific values not provided for all metals)	Levels comparable to urban areas; no health risks identified; reinforced previous findings of minimal HWI impact.	Giné Bordonaba et al. [48]
2011	Soil	Mn most abundant (Mean 316.4 μg/g)	Significant increases in As, Cr, Sn, Tl, V over the 1998-2011 period; health risk assessments indicated no significant carcinogenic or noncarcinogenic risks; 30 soil samples analyzed.	Vilavert et al. [35]
2012	Blood	Pb: 21.7 μg/kg	Decreased Hg, Mn, Pb levels compared to 1998; no additional health risk from HWI emissions; values aligned with international reference values.	Esplugas et al. [38]
2012	Autopsy tissues	Cd highest in kidney (Mean 21.15 μg/g); Pb highest in bone (Mean 1.39 μg/g); As, Be, Ni, Tl, V below detection	Results comparable to general populations; 20 subjects examined; reinforced minimal HWI impact.	Mari et al. [44]
2017	Hair	Levels followed order: Pb > Hg > Ni > Sn > Mn > Cr; As, Be, Tl not detected	Decreased Cr, Pb levels compared to 1998; concentrations similar to other contaminated areas; confirmed minimal HWI influence.	Esplugas et al. [41]
2017	Blood	Cu: 931 μg/kg	No additional health risk from HWI emissions; values aligned with international reference values.	Esplugas et al. [38]
2019	Autopsy tissues	As, Be, Tl, V are not detected; Cr is increasing over time; Pb is decreasing over time	No evidence of increased health risk. Long-term safety confirmed for the monitored population; 20 individuals examined.	García et al. [45]

5. Reviews and Additional Assessments

Vilavert et al. [49] published a review focused on PCDD/F concentrations in soil and vegetation, showing fluctuations but levels similar to other areas, with no health risks, supporting minimal HWI impact. In turn, Giné Bordonaba et al. [48] reported metal levels in 2009-2010, comparable to urban areas, with no health risks, reinforcing previous findings. On the other hand, Nadal et al. [50] prepared a comprehensive review summarizing various years of data, showing stability or decrease in metal levels, with Cr increases noted but no significant risks, concluding minimal HWI influence, but recommending monitoring for Cr(VI).

6. Discussion

The surveillance program around Spain's first (and to date the only) HWI in Constantí (Tarragona County, Catalonia) provides unparalleled insights into the interplay between industrial emissions, environmental persistence, and human health risks for both PCDD/Fs and metals. While the facility's operation did not significantly elevate population exposure beyond baseline levels, the data reveal critical patterns in pollutant dynamics, regulatory effectiveness, and residual health concerns.

Plasma PCDD/F levels dropped by 75% (27.0 to 6.79 pg I-TEQ/g lipid) and dietary intake by 96% (210 pg I-TEQ/day to 8.54 pg WHO-TEQ/day) over two decades. These trends align with EU-wide emission controls and global reductions in combustion-related PCDD/F releases rather than HWI-specific mitigation. Pre- and post-HWI congener profiles in soil/herbage showed no correlation with facility emissions. Instead, higher urban vs. industrial zone PCDD/F levels in breast milk (41% difference) implicated dietary sources (fish, oils) as dominant exposure vectors. The last estimated dietary intake of PCDD/Fs (0.122 pg WHO-TEQ/kg/day) remained below WHO thresholds, with cancer risks for dioxins at 1.1 × 10-5, lower than arsenic's carcinogenic risk (1.1×10^{-4}). Regarding metals, while most of the toxic elements (Pb, Cd, Hg) declined due to EU regulations, Cr levels in autopsy tissues rose by 16% in kidneys and 30-40% in bone over the study period. This contrasts with stable environmental Cr concentrations, suggesting bioaccumulation or unidentified exposure pathways. Arsenic intermittently exceeded carcinogenic thresholds in soils (1.1×10^{-4} risk index), particularly downwind of the HWI, although without clear facility correlation. In turn, blood Pb dropped 70% (3.83 to 2.40 μg/dL), aligning with dietary Pb reductions (48.6 to 39.9 μ g/day). Hair and autopsy data confirmed minimal HWI influence, with metal levels comparable to non-industrial regions.

Despite the above results, residual risks warrant attention. Firstly, chromium speciation. Elevated tissue Cr may involve hexavalent chromium (Cr(VI)), a known carcinogen not routinely monitored in this surveillance program. The lack of speciation data limits risk assessments for kidney and bone cancers. With respect to As, its soil levels periodically have exceeded carcinogenic thresholds. Cumulative exposure via diet (458.5 μ g/day in 2003) remains near provisional tolerable weekly intake (PTWI) limits. Another important issue to be considered is vulnerable subpopulations such as children, pregnant and lactating women, or individuals suffering from certain chronic diseases. For example, children living near the HWI showed Pb levels (0.86 μg/g in hair) exceeding reference values, although still below clinical toxicity thresholds. Moreover, transplacental transfer of PCDD/Fs and Hg remains understudied despite detectable cord blood levels. Another potential issue of notable concern is the synergistic effects among toxicants. The surveillance program did not assess interactions between PCDD/Fs and metals (e.g., co-exposure enhancing oxidative stress or epigenetic modifications), the only pollutants included in the surveillance program. Another weakness of that program concerns the methodological limitations and emerging threats. It includes unmonitored contaminants. The focus on PCDD/Fs and metals overlooked brominated dioxins, microplastics, and volatile organic compounds (VOCs), which modern HWIs emit [51,52]. Epidemiological gaps are another weakness. No cohort studies evaluated cancer incidence or neurodevelopmental outcomes directly tied to HWI proximity [53,54]. Finally, the program has not included the climate change impacts of the HWI. Rising temperatures could remobilize historic metal deposits in soils, altering bioavailability [55,56].

Despite the rather positive results of the surveillance program, there are residual risks. Thus, Cr bioaccumulation and sporadic As exceedances demand targeted monitoring, particularly for Cr(VI) speciation and transgenerational effects. An updated surveillance program should expand biomonitoring to include brominated dioxins, nanoparticle metals, and endocrine disruptors, among other emitted pollutants with potential toxic effects. Cumulative risk assessment is another issue, which means to develop models incorporating PCDD/F-metal interactions, leveraging the EU's Human Biomonitoring Initiative (HBM4EU) protocols [57,58].

On the other hand, as public health priorities, special attention should be paid to vulnerable populations, while future research directions should include longitudinal studies tracking cancer incidence and neurodegenerative disorders in the population living near the HWI [53,54]. Climate resilience is another field of interest. Model how heatwaves and flooding alter metal/PCDD/F mobility from contaminated sites in the area under the influence of the emissions of the HWI [59,60].

The HWI in Constantí, Catalonia—operational since 1999—serves as a critical case study for evaluating health risks from hazardous waste incinerators. Despite adhering to the EU's Industrial Emissions Directive limit of 0.1 ng TEQ/Nm³ for PCDD/Fs, the safety of this threshold remains unproven, with no clear evidence confirming it as a risk-free exposure level. Current risk assessments focus narrowly on heavy metals (e.g., As, Cr, Cd) and PCDD/Fs, neglecting unmonitored or unidentified chemicals and potential synergistic effects between carcinogens, creating significant knowledge gaps. Existing epidemiological studies on health impacts of waste incinerators in general, and specifically for HWIs are certainly scarce, being limited by methodological flaws, inconsistent findings, and insufficient long-term data. For instance, carcinogenic effects often emerge decades after exposure, yet the 20-year operation period of the Constantí HWI has not prompted comprehensive local epidemiological research. Authorities are urged to prioritize such studies, integrating biomarkers, socioeconomic factors, facility-specific data (e.g., technology, maintenance), and residential duration to clarify risks. In relation to this, the analogy to tobacco exposure—where no safe level exists— underscores concern about permitting any emissions of carcinogens. Rigorous public health surveillance and updated research designs are essential to address uncertainties and protect communities near waste incinerators.

On the other hand, we would like to note that the lack of air quality monitoring in the surveillance program has limited the ability to fully assess atmospheric contributions from the HWI. Although recent data suggest that PCDD/F levels in ambient air in Catalonia have decreased, targeted air quality monitoring near the HWI is recommended to confirm these trends and assess implications for nearby residents.

7. Conclusions and Recommendations

Based on the studies summarized here, all conducted by a single research group as part of the HWI surveillance program, preliminary conclusions would suggest that the facility might not pose significant environmental concerns or health risks with respect to the specific pollutants monitored (PCDD/Fs and a limited set of metals). However, this narrow focus and the reliance on a single research group introduce potential bias and limit the ability to draw conclusions about the HWI's overall impact. Modern HWIs emit a complex mixture of pollutants, including volatile organic compounds (VOCs), brominated dioxins, microplastics, and nanoparticles, which were not included in the surveillance program. Therefore, the findings should not be interpreted as definitive evidence of the HWI's overall safety. Additionally, the lack of comprehensive epidemiological studies directly assessing health outcomes in populations near the HWI further limits the conclusions. Consequently, future research should expand monitoring to include a broader range of pollutants and develop models that incorporate interactions between different contaminants to better understand cumulative health risks. To address these limitations, the following actions are recommended:

1. Expand risk assessments to include emerging chemicals and chemical interactions.

2. Implement long-term biomonitoring and transparent public health reporting (including the expanded list of pollutants).

3. Conduct targeted epidemiological studies to assess health impacts near the Constantí's HWI.

4. Re-evaluate EU emission limits with evidence-based health safeguards (based on the findings of the expanded monitoring and epidemiological studies).

Critically, potential synergistic interactions among the complex mixture of chemicals emitted by the HWI were not considered in these studies, representing a significant knowledge gap that must be addressed in future research.

Author Contributions

All three authors contributed equally to the development of this paper. Conceptualization, J.L.D., J.R., and M.S.; methodology, J.L.D., J.R., and M.S.; formal analysis, J.L.D., J.R., and M.S.; writing—original draft preparation, J.L.D., J.R., and M.S.; writing—review and editing, J.L.D., J.R., and M.S. All authors have read and agreed to the published version of the manuscript. The tasks of writing, data curation, review, and editing were shared among the authors, with each author actively participating in every stage of the manuscript preparation.

Funding

This paper received no financial support or funding for its preparation.

Institutional Review Board Statement

Not applicable

Informed Consent Statement

Not applicable.

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within articles reviewed or they supplementary materials..

Acknowledgments

We sincerely thank the numerous scholars and researchers whose foundational work and insightful contributions have laid the groundwork for continued exploration and progress in this area of study.

Conflicts of Interest

There are no conflicts of interest.

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