Review Article

Evolution of Occupational Health Risks Among Waste Incinerator Workers: A Four-Decade Review

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Occupational health risks among waste incinerator workers have undergone marked changes over the last four decades, paralleling advances in technology, regulatory frameworks, and waste composition. This comprehensive review synthesizes studies from 1980 to 2025, providing a historical lens on exposure trends, disease outcomes, and interventions in municipal, medical, and hazardous waste incineration settings worldwide. Early investigations highlighted severe exposures to dioxins and furans (PCDD/Fs), and heavy metals, resulting in high rates of respiratory illness, dermatological conditions, and increased cancer risk. While modern emission controls have greatly reduced overall exposures, persistent health risks, especially respiratory, cardiovascular, and neurological, remain evident, particularly in outdated facilities and developing regions. The emergence of new threats, including brominated flame retardants, perfluorinated compounds, and microplastics, highlights the evolving complexity of workplace hazards as waste streams change. Geographic disparities in risk and protection reflect gaps in technology transfer, regulatory stringency, and resource allocation. Despite substantial progress, this review finds that the complete elimination of occupational hazards in incineration work remains elusive. Integrated protective strategies, long-term cohort surveillance, and research into emerging contaminants are recommended to sustain and advance worker health globally.

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Introduction

The industrial-scale incineration of waste materials emerged as a significant waste management strategy in developed countries during the 1970s, initially driven by land scarcity and energy recovery considerations[1][2]. However, early recognition of potential health risks associated with emissions from these facilities led to concerns about occupational exposures for the workers operating them. The first comprehensive occupational health studies of waste incinerator workers began in the early 1980s, coinciding with growing awareness of the health effects of polychlorinated dibenzo-*p*-dioxins and furans (PCDD/F, named as "dioxins") and other combustion-related pollutants[3][4].

The evolution of waste incineration technology over the past four decades has been marked by significant improvements in combustion efficiency, emission control systems, and operational practices[5][6]. Modern waste-to-energy facilities bear little resemblance to the rudimentary incinerators of the 1970s and 1980s, incorporating sophisticated air pollution control devices, continuous emission monitoring, and advanced process control systems[7][8]. Despite these technological advances, questions about occupational health risks persist, particularly given the long latency periods for many health effects and the introduction of new contaminants in waste streams[9]. Furthermore, the changing composition of municipal solid waste (MSW), with increasing volumes of plastics and electronic waste, creates new and poorly characterized combustion by-products[10].

The occupational health research in this field has evolved from early descriptive studies reporting gross exposures[11], to sophisticated biomonitoring investigations employing state-of-the-art analytical techniques[12]. Early studies focused primarily on PCDD/F exposure, reflecting the intense scientific and regulatory attention these compounds received following events such as the Seveso disaster and the establishment of dioxin as a human carcinogen[13]. Subsequent research expanded to include heavy metals, particulate matter (PM), and a growing list of organic pollutants generated during the incineration process[14][15][16].

The diversity of waste types processed in incineration facilities has also influenced the evolution of occupational health research. Municipal solid waste incinerators (MSWIs), which handle the broadest range of materials, have been most extensively studied[17][18][19][20][21][22]. In turn, medical waste incinerators (MWIs), often operating at smaller scales but handling materials with unique contamination risks, have received focused attention since the 1990s[23][24]. However, the COVID-19 pandemic led to a

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significant increase in the generation of certain types of medical waste, potentially altering exposure profiles for workers in facilities that incinerated this material[25]. On the other hand, hazardous waste incinerators (HWIs), typically subject to the most stringent regulatory controls, have been studied less extensively but often reveal the highest exposure levels[26][27][28][29].

Geographic variations in technology, regulation, and waste composition have produced a complex global picture of occupational health risks. Studies from Europe, North America, and Japan generally reflect more advanced emission control technologies and stricter regulatory frameworks, while investigations from developing countries often report higher exposure levels and more severe health effects[30][31][32][33]. This geographic disparity highlights the ongoing relevance of occupational health research in this field, as global waste generation continues to grow and incineration capacity expands, particularly in developing economies.

The present comprehensive review synthesizes various decades of research on occupational health risks for waste incinerator workers. It examines the evolution of exposure patterns, health outcomes, and protective measures across different facility types, geographic regions, and time periods, providing historical context for current understanding, while identifying persistent knowledge gaps and emerging research priorities.

Methods

This review has been based on an examination of the scientific literature belonging to occupational health in waste incineration facilities. The review focuses on papers published between the 1980's and September 2025, which illustrate key trends in exposure assessment, health effect reports, and the evolution of protective measures. This is a comprehensive review that does not adhere to the systematic review or meta-analysis protocol, and no quantitative synthesis of data across studies is attempted. The goal is to provide a critical analysis of the state of knowledge based on the available body of scientific evidence.

This comprehensive narrative review approach was chosen over a systematic review or meta-analysis protocol because of the substantial heterogeneity in study designs, exposure assessment methods, health outcome measurements, and facility types across the literature. The goal was to provide a critical synthesis and analysis of the state of knowledge rather than quantitative pooling of effect estimates.

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Literature Search Strategy

The databases used were PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar. Additional research was conducted in specialized databases and national occupational health agency reports. The search strategy employed a comprehensive combination of terms including: ("waste incineration" OR "municipal solid waste" OR "medical waste" OR "hazardous waste" OR "waste-to-energy" OR "thermal treatment" OR "combustion facility") AND ("occupational exposure" OR "worker" OR "employee" OR "personnel" OR "staff") AND ("health effect" OR "biomarker" OR "dioxins" OR "PCDD/F" OR "heavy metal" OR "particulate matter" OR "respiratory" OR "cancer" OR "mortality"). The search was limited to human studies.

Inclusion and Exclusion Criteria

Studies included were those examining occupational exposure or health effects in workers at waste incineration facilities, regardless of waste type or facility size. Both quantitative and qualitative studies were included. No restrictions were placed on study design, sample size, or publication type, initially. Specifically, the following inclusion criteria were applied: a) English-language publications were prioritized, although non-English publications with English abstracts indicating highly relevant content were considered, b) all empirical study designs were eligible, including cohort, case-control, cross-sectional, and case series studies, c) study populations comprised workers at any type of waste incineration facility regardless of job category or employment duration, d) facility types included municipal solid waste incinerators (MSWIs), medical waste incinerators (MWIs), and hazardous waste incinerators (HWIs), and e) no geographic restrictions were applied. By contrast, those studies focusing exclusively on environmental emissions without occupational data, community exposure assessments without worker data, and purely theoretical or modeling studies without empirical data, were excluded. However, comprehensive reviews and meta-analyses were retained for reference synthesis. Studies on open burning of waste were also excluded, as the exposure scenarios are not comparable to controlled incineration facilities.

Methodological Limitations and Study Quality Considerations

Several methodological constraints must be considered when interpreting the findings of this review. A first concern relates to potential publication bias, given that studies reporting statistically significant or positive associations tend to be published more frequently than those yielding null or inconclusive results. Geographic representation also remains uneven, with most available evidence originating from industrialized regions such as Japan, the United States, and Western Europe, while data from developing countries, where occupational exposures may be greater, are comparatively scarce. Substantial heterogeneity in study design, exposure assessment protocols, and outcome definitions further restricts comparability among investigations. Moreover, numerous individual studies presented intrinsic methodological weaknesses, including small sample sizes, incomplete adjustment for potential confounders (such as smoking, socioeconomic status, and co-exposures from other occupations), and reliance on cross-sectional approaches that hinder causal inference. Temporal comparisons are further complicated by changes in analytical methodologies over the review period, as earlier investigations commonly used techniques with lower specificity and higher detection limits than those currently available. Finally, because this is a comprehensive narrative review rather than a systematic review, it does not incorporate formalized study quality appraisal or meta-analytic aggregation of quantitative results.

Results

Literature Overview and Study Characteristics

Geographically, most studies originated from developed countries, with Japan, United States, Germany, Italy, and Spain contributing the most investigations[34][28][35][12][16][36][37][38]. However, important studies from countries such as China, India, and Brazil often reported more severe exposure conditions[39][40][41][42][43].

Research on occupational health in waste incineration has expanded considerably since the first studies in the 1980s. Early investigations were predominantly conducted in Western Europe and North America, focusing on MSWIs[3][44]. Over time, the geographic scope has widened, and research has diversified to include MWIs and HWIs, reflecting the global expansion of this waste management technology[45][29][19].

Evolution of PCDD/F Exposure Assessment

Early Studies

The earliest occupational studies of waste incinerator workers emerged from concerns about PCDD/F exposure following high-profile environmental contamination events. Biomonitoring studies reported

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serum PCDD/F concentrations substantially elevated compared to the general population, establishing the pattern of exposure-duration relationships that would become a consistent finding across subsequent investigations[11]. PCDD/F congener patterns, typical of combustion sources, were found, distinguishing occupational exposure from background environmental contamination. In Germany, Angerer et al.[34] conducted a study with incinerator workers, detecting internal exposure to organic substances with elevated mean serum concentrations across multiple facilities, with maintenance workers and ash handlers showing the highest PCDD/F levels. A seasonal variation in exposure was also noted, with higher concentrations of organic substances during winter months, which was attributed to increased waste throughput and more frequent maintenance activities[34].

Technology Transition Period

The mid-1990s marked a crucial transition period as emission control technologies began widespread implementation. Studies during this period noted the effectiveness of technological improvements, while revealing persistent exposure risks in facilities with inadequate controls. Longitudinal monitoring of Japanese incinerator workers reported substantial reductions in serum PCDD/F concentrations across different operational patterns[46][47][48][49]. However, even in upgraded facilities, worker concentrations of dioxins remained elevated compared to community background levels[50].

Modern Era Studies

Recent studies reflect both improved emission control technologies and more sophisticated analytical techniques, employing high-resolution mass spectrometry and expanded congener profiles, providing more detailed exposure characterization[51][52][53][54]. Table 1 summarizes the temporal evolution of PCDD/F levels across different time periods, facility types, and geographic regions, highlighting the substantial reductions achieved through technological improvements while noting persistent exposure concerns in developing countries.

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Time Period	Country/Region	Incinerator Type	Key Findings	References
Early Studies (1980-1995)	USA	Municipal Waste	Severe occupational exposure; exposure-duration relationships established	[11]
	Germany	Municipal Waste	Maintenance workers and ash handlers most exposed; seasonal variations noted	[34]
Technology Transition (1995-2005)	Japan	Municipal Waste (continuous)	60-80% reduction following emission control installation	[46]
	Japan	Municipal Waste (intermittent)	Lower levels in intermittent vs. continuous operation	[47]
	Japan	Medical waste	Medical waste facilities showed lower levels than municipal waste incinerators	[49]
Modern Era (2005-2025)	Spain	Hazardous waste	Substantial reduction but still elevated levels vs. background	[55]
	Korea	Industrial/Municipal Waste	Industrial waste workers showed higher exposure	[32]
	Spain	Municipal Waste	Longitudinal study showing modest increase during operation	[56]
	China	Municipal Waste	Developing country levels comparable to 1980s-1990s developed countries	[39]
	Japan	Municipal Waste	Modern Japanese facilities show continued variability	[37]
			Background Population Levels: 6-28 pg WHO-TEQ/g lipid (various studies)	

Table 1. Evolution of PCDD/F Exposure Levels in Waste Incinerator Workers by Time Period

Biomonitoring studies of workers at modern waste-to-energy facilities found lower mean serum concentrations compared to historical values but still high in comparison to those of the general populations[55][57][12]. Long-term follow-up studies have reported continued decline in serum PCDD/F concentrations over extended periods, while also revealing persistent elevation in certain congeners, particularly those with longer half-lives, highlighting the lasting impact of historical occupational exposure[56].

Recent studies from developing countries continue to report concerning exposure PCDD/F levels. Elevated serum PCDD/F concentrations and body burden have been found in Chinese incinerator workers, with levels and influencing factors comparable to those observed in developed countries during the 1980s-1990s[39]. Quantitative risk assessment studies have noted ongoing occupational exposure concerns in the waste incineration industry[58]. These findings highlight the global nature of occupational health risks and the importance of technology transfer and regulatory harmonization.

Heavy Metal Exposure

Lead exposure in waste incinerator workers has been assessed since the early 1990s, reflecting the ubiquitous presence of lead-containing materials in municipal waste streams. Early studies reported elevated blood lead levels in US incinerator workers, with ash handlers and maintenance personnel showing the highest lead concentrations[59]. Temporal trends in lead exposure have generally shown declining patterns in developed countries, paralleling reductions in lead use and improved emission controls. However, significant exposure continues to be in many facilities. Biomonitoring studies have reported metals exposure (including lead) in workers at waste-to-energy incinerators, with longitudinal studies showing continued elevated levels despite advanced emission control systems[14][16]. Recent studies have identified emerging sources of lead exposure, particularly from electronic waste components increasingly present in MSW. Exposure to heavy metals and its association with DNA oxidative damage has been reported in waste incinerator workers, with levels substantially higher in facilities processing mixed waste streams[60][43].

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In turn, cadmium exposure patterns reflect both direct inhalation of particulate matter and secondary exposure through contaminated surfaces and ash handling. Assessments of cadmium exposure in European incinerator workers have documented high cadmium concentrations, notably higher compared to those for reference populations[14][16]. Studies have consistently identified job category as a primary determinant of cadmium exposure, with ash handlers, maintenance workers, and furnace operators showing the highest levels. Substantially elevated concentrations of this metal in workers, were found compared to administrative personnel at the same facilities[61]. Advanced analytical techniques have been employed to characterize multiple metal species in biological samples from workers, providing insights into bioavailability and toxicological significance[45].

On the other hand, mercury exposure in waste incinerator workers presents unique challenges due to the volatile nature of mercury compounds and their potential for both inhalation and dermal absorption. Early studies found elevated concentrations in workers, with peak levels observed during periods of high medical waste incineration[62]. While the phase-out of mercury-containing medical devices and thermometers has substantially reduced exposure levels in many developed countries[63]., persistent exposure continues from dental amalgam disposal, fluorescent lamp breakage, and electronic waste processing. Continued mercury exposure in workers at facilities processing medical and electronic waste has been reported[14][61].

Recent studies have also started to characterize exposure to less common metals like antimony and thallium from the incineration of electronic waste, although their health significance in this occupational context is not yet fully understood[14][64].

Respiratory Health Effects

Acute Respiratory Effects

Acute respiratory effects have been observed since the earliest occupational health studies of waste incinerator workers. Bresnitz et al.[3] conducted one of the first respiratory health assessments, reporting increased prevalence of cough, wheezing, and shortness of breath in New Jersey incinerator workers. Subsequent studies confirmed these patterns across diverse populations and facility types, reporting elevated respiratory symptom prevalence rates for chronic cough, phlegm production, and dyspnea in European MSWI workers. Symptom severity correlated with employment duration and job category, with maintenance workers and ash handlers showing the highest rates[17][65]. Cross-sectional studies utilized standardized respiratory questionnaires to assess symptoms in workers, detecting elevated prevalence compared to unexposed controls and examining comprehensive morbidity patterns[66].

Pulmonary Function Changes

Pulmonary function testing has revealed consistent patterns of airway obstruction and restrictive changes in exposed workers. Early spirometry studies found reduced forced expiratory volume and forced vital capacity in German incinerator workers, with changes correlating with employment duration and smoking status[34]. Moreover, longitudinal studies provided insights into respiratory function changes among waste incinerator workers, with assessments founding patterns of pulmonary function decline[65]. These changes persisted after adjustment for age, smoking, and anthropometric factors. Advanced pulmonary function testing has revealed more subtle but clinically significant changes. Papageorgiou et al.[67] employed comprehensive respiratory assessments to demonstrate functional changes in workers, suggesting effects consistent with chronic exposure to particulate matter and toxic gases

Dermatological Effects

Dermatological effects have been consistently reported since early occupational studies, reflecting both direct contact with contaminated materials and systemic absorption of toxic compounds[24]. Early studies reported chloracne-like lesions and dermatological morbidities in workers with high PCDD/F exposure, establishing direct links between exposure to these compounds and characteristic skin changes[68]. Contact dermatitis represents the most common dermatological effect. Dermatological examinations have found allergic contact dermatitis and sharp injuries in exposed workers compared to controls, with dermatological morbidities being particularly prevalent among MWI workers[24]. Patch testing revealed sensitization to multiple industrial chemicals commonly present in incinerator environments[69].

Cardiovascular Effects

Cardiovascular effects in waste incinerator workers have received research attention, particularly following recognition of cardiovascular toxicity associated with particulate matter and PCDD/F exposure. In this sense, early studies already reported prevalence of hypertension and arrhythmias in Swedish workers[44][70]. Subsequent cross-sectional studies also reported increased blood pressure, altered cardiac parameters, and electrocardiographic changes consistent with cardiovascular stress in exposed populations[66]. Beyond hypertension, recent research has explored subclinical effects. Exposure to particulate matter (PM2.5) and metals has been linked to systemic inflammation and endothelial dysfunction, which are established precursors to atherosclerosis and cardiovascular events[71].

Neurological and Neurobehavioral Effects

Neurological effects have been less extensively studied but represent an emerging area of concern, particularly given documented neurotoxicity of several compounds present in incinerator emissions. The neurotoxic potential of exposure mixtures in incinerators, particularly from metals like lead and manganese, and organic compounds such as polycyclic aromatic hydrocarbons (PAHs), remains a concern[72]. Ott et al.[73] found an increased prevalence of headaches, memory problems, and concentration difficulties in incinerator workers. Neurobehavioral testing has also revealed changes in exposed populations. Standardized test batteries have been employed to assess workers, reporting reduced performance on tests of attention, memory, and psychomotor function compared to matched controls[74]. Mental health status of MSWI workers was also examined, comparing outcomes with office workers[75]. Interestingly, health administration personnel exhibited poorer mental health than those employed at MSWI facilities, indicating that the regular stress experienced by health administrators surpassed the additional worry MSWI workers faced regarding potential PCDD/F exposure.

Genetic and Molecular Effects

Genetic toxicity studies have shown DNA damage in lymphocytes and granulocytes in workers exposed to PAHs and other combustion products[76], which has been also found in recent studies employing gene expression profiling as new real-time assays in human biomonitoring of waste-to-energy plant workers[51]. On the other hand, increased cytochrome P4501B1 gene expression was also demonstrated in peripheral leukocytes of workers, as well as associations between gene expression and blood lipid levels[77][78]. These findings suggest molecular-level effects of occupational exposure.

Immunological and Reproductive Effects

The evidence for immunotoxic and reproductive effects is less consistent than for other endpoints. While some studies like those of Oh et al.[79] reported alterations in immune parameters and potential

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reproductive toxicity indicators, larger cohort studies are still needed to confirm these associations and establish causal relationships.

Cancer and Mortality Studies

Lung Cancer

Lung cancer represents the most extensively studied cancer outcome in waste incinerator workers, reflecting both the respiratory route of exposure and the carcinogenicity of several compounds in incinerator emissions. The first mortality study was conducted by Gustavsson[44], who observed elevated standardized mortality ratios for lung cancer in Swedish incinerator workers. Subsequent studies also found an increased risk of esophageal cancer among workers exposed to combustion products[70]. In turn, larger retrospective cohort studies reported mortality patterns among workers at municipal waste incinerators, providing more definitive evidence on cancer outcomes[80]. Moreover, recent systematic reviews and meta-analyses have synthesized cancer evidence across studies, documenting cancer risks in relation to environmental waste incinerator emissions through comprehensive analysis of case-control and cohort studies[81].

All-Cause Mortality

All-cause mortality studies have provided insights into overall health impacts of waste incineration work. In relation to this, large-scale studies have reported health effects of chronic exposure to PCDD/F and their accumulation in workers, with survey results examining mortality patterns[35][82][62][36].

Biomarker Studies and Mechanistic Investigations

PCDD/F and PCB Analysis

Comprehensive dioxin and dioxin-like PCB profile studies have been conducted in serum of industrial and municipal waste incinerator workers, providing detailed characterization of exposure patterns[32][12]. Cross-sectional analyses have examined PCDD/F concentrations and health effects in municipal and private waste incinerator workers[37]. Studies have also examined isomer patterns and elimination of PCDD/F in workers exposed at municipal waste incineration plants[38]. The effects of PCDD/F on

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metabolism of estrogens in waste incinerator workers were also investigated, providing insights into endocrine disruption mechanisms[83].

Oxidative Stress and Metabolic Effects

Oxidative stress has been detected in blood of workers at incineration facilities, with studies documenting comprehensive biomarker patterns[84]. Recent studies have employed metabolomics approaches to characterize oxidative stress pathways in these workers[42].

Emerging Contaminants Assessment

Lu et al.[85] reported internal exposure of phthalate metabolites and bisphenols in waste incineration plant workers with associated health risks. Quantification of bisphenol analogues in blood and urine samples of workers has expanded understanding of emerging contaminant exposure[86]. A previous analysis of urinary metabolites of PAHs in incineration workers provided insights into PAHs exposure patterns[87]. Recent studies measuring urinary metabolites of phosphate flame retardants in workers found associations of these compounds with oxidative stress[88][42]. A biomonitoring study of hydroxylated PAH metabolites (ten urinary hydroxylated polycyclic aromatic hydrocarbon) was recently conducted in workers at waste-to-energy incinerators in Turin, Italy[52]. In the incinerator workers, no significant increases in metabolite concentrations were observed because of occupational exposure.

Table 2 provides an overview of health effects across different organ systems and the corresponding biomarkers used for exposure assessment. The diversity of health outcomes across multiple study populations reinforces the systemic nature of occupational exposures in waste incineration facilities. The progression from early symptom-based assessments to sophisticated molecular biomarker studies reflected in Table 2 shows the evolution of occupational health research methodology. Notably, respiratory effects remain the most consistently reported outcome across all study populations, while emerging research on genetic and molecular effects provides mechanistic insights into exposure pathways and early biological responses.

Health Effect Category	Study Population	Main Findings	Biomarkers/Measurements	References
Respiratory Effects	US municipal waste incinerator workers	Cough, wheezing, dyspnea	Symptom questionnaire, spirometry	[3]
	French municipal waste incinerator workers	Chronic cough, phlegm, dyspnea	Cross-sectional health assessment	[66]
	French incinerator workers	Reduced FEV1 and FVC, correlation with employment duration	Pulmonary function testing	[65]
	Review of multiple studies on MSWI workers	Consistent respiratory symptom elevation across studies	Meta-analysis of respiratory outcomes	[17]
Heavy Metal Exposure	US incinerator workers	Blood lead levels highest in ash handlers	Blood lead levels	[59]
	Italian workers (longitudinal)	Elevated cadmium, lead, mercury; declining trends over time	Comprehensive metal biomonitoring	[14]
	Chinese workers	Heavy metal exposure associated with DNA oxidative damage	Blood metals, oxidative stress markers	[43]
Dermatological Effects	Egyptian medical waste incinerators workers	Contact dermatitis, chloracne-like lesions	Dermatological examination, patch testing	[24]
Genetic/Molecular Effects	Korean workers	Increased DNA damage in lymphocytes and granulocytes	Comet assay, micronucleus test	[76]
	Taiwanese workers	Increased CYP1B1 gene expression in peripheral leukocytes	Real-time PCR gene expression	[77]

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Health Effect Category	Study Population	Main Findings	Biomarkers/Measurements	References
	Italian workers	Altered gene expression profiles in exposed workers	RNA sequencing, gene profiling	[51]
Immunological Effects	Korean workers	Altered immune parameters, reproductive toxicity indicators	Immune function tests, hormone assays	[79]
Cancer/Mortality	Swedish workers	Excess lung cancer, ischemic heart disease	Mortality registry linkage	[44]
	Italian workers	Increased prostate cancer mortality	Retrospective cohort study	[80]
	Meta-analysis	Increased lung cancer risk	Systematic review and meta-analysis	[81]
Emerging Contaminants	Spanish hazardous waste incinerator workers	Elevated bisphenol analogues in blood and urine	LC-MS/MS analysis	[86]
	Chinese workers	Phthalate metabolites and bisphenols exposure	Urinary metabolite analysis	[85]
	Chinese workers	Organophosphate ester exposure (OPE), oxidative stress associations	Urinary OPEs, oxidative biomarkers	[42]

Table 2. Health Effects and Biomarker Studies in Waste Incinerator Workers

Protective Measures and Intervention Studies

Personal Protective Equipment

Salazar er al.[89] evaluated the factors affecting hazardous waste workers' use of respiratory protective equipment. A substantial variability in protection factors was noted, depending on equipment type, fit testing quality and compliance rates. In turn, Raemdonck et al.[90] examined exposure of maintenance workers to dioxin-like contaminants during temporary shutdowns, providing insights into high-risk exposure scenarios. Exposure assessments of maintenance workers before and after annual maintenance noted the effectiveness of protective measures during high-risk activities[91].

Engineering Controls and Monitoring

The evolution of engineering controls in waste incineration facilities represents one of the most significant factors in reducing occupational exposure levels over the past four decades. This section examines the technologies used historically and currently, their effectiveness in reducing worker exposures, their limitations, and the substantial differences in implementation between developed and developing countries.

To evaluate engineering control effectiveness, Maître et al.[61] conducted a survey aimed at air and biological monitoring of workers for exposure to particles, metals, and organic compounds. Occupational exposure in two MSWIs was well below regulatory limits, but airborne particles and metals were much higher at these sites than at control locations. The principal sources were cleaning tasks for particles and residue management for metals. It was concluded that biological monitoring might be useful for assessing long-term personal exposure, but only air monitoring reliably identifies and helps to control the main emission sources. Comparisons of PCDD/F levels in surrounding environments and workplaces have also provided insights into emission control effectiveness[92].

Despite their effectiveness, modern emission control systems have important limitations. Capital costs for comprehensive multi-stage control systems represent a substantial financial barrier for resource-limited settings. Operating costs, including activated carbon consumption, filter bag replacement, and energy requirements, mean various millions of dollars/euros annually. Technical complexity requires highly trained maintenance personnel and sophisticated monitoring systems. Control system failures can result in emission spikes that expose workers to elevated pollutant concentrations. Emerging contaminants such as PFAS, nanoplastics, and novel brominated compounds may not be efficiently captured by current control technologies designed primarily for dioxins and metals. Maintenance activities, particularly during annual shutdowns, when workers access contaminated areas for repairs, create high-exposure scenarios that engineering controls cannot fully prevent.

Health Surveillance

Biomonitoring

Systematic biomonitoring and exposure assessment programs have been implemented for people living near or working at waste incinerators[45][12]. Biological monitoring of metals and organic substances in hazardous-waste incineration workers has been conducted[27][93] while follow-up studies have examined levels of metals and organic substances in workers over extended periods[55][57]. Body burden monitoring of dioxins and other organic substances in workers has provided longitudinal assessment of exposure patterns[12].

International Surveillance Efforts

Cross-sectional studies have examined the impact waste incinerators on human exposure to PCDD/F, PCBs, and heavy metals across multiple countries[94]. Health surveys on workers and residents near municipal and industrial waste incinerators have been conducted in various countries[95][31][55][57][12][62].

Discussion

Scientific Consensus and Areas of Uncertainty

More than four decades of research have established a solid scientific consensus on several key aspects of occupational exposure in waste management and related industrial settings. Modern emission control technologies have shown reduced worker exposures, typically resulting in 80–90% declines in serum PCDD/F concentrations and 50–70% reductions in blood lead levels following technological upgrades. These exposure decreases have been observed across diverse facility types and geographic regions. Respiratory outcomes exhibit the most robust and reproducible association with occupational exposure, with prevalence rates two to three times higher among exposed workers compared to reference populations, independent of temporal or regional variation. Employment duration shows a clear dose–response relationship with biomarkers of exposure and selected health outcomes, supporting the concept of cumulative exposure effects. Moreover, occupational role strongly influences exposure magnitude, with maintenance personnel and ash handlers consistently exhibiting the highest exposure levels across studies.

In contrast, several areas remain unresolved or continue to be debated. The magnitude of cancer risk among workers at modern facilities, employing advanced emission controls, remains uncertain due to inconsistent epidemiological evidence and broad confidence intervals. Although meta-analyses suggest elevated risks, substantial heterogeneity across studies precludes definitive conclusions. The quantitative effectiveness of specific personal protective equipment (PPE) remains poorly characterized, as few controlled investigations have compared different PPE configurations under field conditions. Studies addressing reproductive and immunological outcomes report variable findings, ranging from significant alterations to null associations. Likewise, the potential health implications of emerging contaminants (including PFAS, microplastics, and newly developed flame retardants) are largely undetermined, with research in these fields still limited. Finally, the selection of optimal biomarkers and analytical strategies for biomonitoring remains a matter of scientific debate, particularly regarding the assessment and interpretation of low-level exposures to novel contaminants.

Methodological Challenges in Field Measurements

Field investigations of occupational exposure are constrained by several methodological limitations that affect the accuracy, reproducibility, and comparability of exposure metrics. Temporal variability is often pronounced, with exposure levels fluctuating by one to two orders of magnitude depending on operational phase (e.g., routine operation versus startup or shutdown), maintenance activities, and variations in waste composition. Although personal air sampling provides time-integrated exposure estimates, it fails to capture short-term peaks associated with specific high-risk tasks. By contrast, area air sampling cannot adequately reflect individual exposures, particularly among workers who move frequently between different process zones.

Biomonitoring offers a more direct measure of internal dose but is complicated by substantial inter-individual variability in metabolic capacity and elimination kinetics, as well as by background exposure from environmental or lifestyle sources. Moreover, the persistence of certain compounds (such as selected PCDD/F congeners) can mask short-term exposure changes due to their long biological half-lives. Analytical precision may be further influenced by matrix characteristics of biological samples (e.g., lipid content or protein binding), necessitating rigorous quality assurance procedures. Historical trends in analytical technology introduce additional uncertainty: earlier studies often employed methods with lower sensitivity and specificity, limiting the comparability of results obtained over time. Establishing robust dose–response relationships remains particularly challenging due to the complex nature of

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exposure mixtures, co-occurrence of multiple pollutants, and the likelihood of additive, synergistic, or antagonistic interactions among them. Finally, epidemiological interpretation can be biased by workforce dynamics, including the healthy worker effect, reassignment of symptomatic individuals to lower-exposure jobs, and survival bias in long-term cohorts, all of which may lead to systematic underestimation of current health risks.

Evolution of Occupational Health Knowledge

Various decades of research on waste incinerator worker health have demonstrated a clear evolution in both exposure patterns and health outcomes, closely paralleling developments in incineration technology and regulatory frameworks[9][16]. The earliest studies from the 1980s reported severe exposures to PCDD/F and other combustion pollutants[11][34], with serum PCDD/F concentrations often exceeding 500 pg WHO-TEQ/g lipid and widespread respiratory and dermatological effects[3]. The implementation of advanced emission control technologies beginning in the 1990s produced substantial reductions in many exposure metrics[7]. Modern waste-to-energy facilities typically achieve PCDD/F emissions below regulatory limits, compared to much higher emissions from earlier facilities[50][55][12]. These technological improvements have translated into meaningful reductions in worker exposure levels[37][38].

Persistent Health Risks and Emerging Concerns

Despite technological advances, occupational health risks persist in the waste incineration industry[17][14][62]. Modern biomonitoring studies continue to high exposure levels of dioxins and heavy metals compared to background populations[39][43], and health surveillance programs identify ongoing respiratory, dermatological, and systemic health effects in exposed workers[65][24].

The emergence of new contaminants in waste streams poses ongoing challenges for occupational health protection[10]. Substances such as brominated flame retardants, PFAS, and pharmaceutical residues were not present in significant quantities when recent measurements were carried out[86][85]. Nevertheless, the potential adverse health effects of chronic exposure to these emerging contaminants remain poorly characterized, which means a significant knowledge gap[42][88]. In turn, electronic waste (e-waste) represents a particular challenge given its complex chemical composition and increasing prevalence in municipal solid waste[52]. The co-incineration of e-waste with conventional municipal waste may create novel exposure scenarios not adequately addressed by current protection measures.

Geographic Disparities and Global Health Equity

The global expansion of waste incineration, particularly in developing countries, has created significant disparities in occupational health protection[30]. Workers in those countries often face exposure levels and health risks comparable to those found in developed countries 20-30 years ago[39]. This pattern reflects limited access to advanced emission control technologies, less stringent regulatory frameworks, as well as inadequate resources for worker protection programs[32]. Table 3 illustrates these geographic disparities in both exposure levels and protective measure implementation, revealing substantial variations in occupational health protection across different regions and developmental contexts. The temporal and geographic patterns shown in Table 3 highlight critical gaps in global health equity within the waste incineration industry. While developed countries have implemented surveillance programs and achieved substantial exposure reductions, recent studies from China and developing countries report exposure levels comparable to those observed in developed countries during the 1980s-1990s. This disparity emphasizes the urgent need for technology transfer, capacity building, and harmonized international standards to ensure adequate protection for all waste incinerator workers regardless of geographic location.

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Region/Country	Time Span	Key Study Characteristics	Protective Measures Evaluated	Current Status
Japan	2000–2015	Comprehensive dioxin monitoring; technology upgrades documented. Key studies: Kumagai et al.[46][47][50][48], Kitamura et al.[35], Yamamoto et al.[37][38], Takata[36]	Engineering controls, biomonitoring programs; National surveillance program established	Advanced emission controls, declining exposure trends; annual medical examinations with serum PCDD/F monitoring
Spain	2000–2019	Hazardous and municipal waste facilities; longitudinal follow-up. Key studies: Mari et al.[55][57][12], González et al.[86]	Integrated intervention programs; advanced biomonitoring techniques	Modern emission controls, continued surveillance; engineering improvements, enhanced PPE, worker training
European countries	1992–2020	Early exposure documentation; multi-country comparisons. Key studies: Angerer et al.[34], Fierens et al.[94], Bena et al.[45][14]	Biological exposure indices (BEI) established; cross-border exposure assessments	Harmonized EU occupational standards; Serum-based surveillance thresholds
Sweden/USA	1989–2001	Early health effects studies; respiratory focus. Key: Gustavsson[44], Bresnitz et al.[3], Malkin et al.[59], Salazar et al.[89]	PPE effectiveness evaluation; occupational hazard identification	Regulatory frameworks established; respiratory protection programs
Korea	2003–2009	Comprehensive exposure profiling; health surveys. Key studies: Leem et al.[31], Oh et al.[79], Park et al.[32], Sul et al.[76]	Limited protective measure evaluation; industrial vs. municipal comparisons	Developing regulatory framework; basic PPE and engineering controls

Region/Country	Time Span	Key Study Characteristics	Protective Measures Evaluated	Current Status
China	2020-2023	Recent studies showing high exposures; emerging contaminants. Key studies: Peng et al.[39], Yang et al.[43], Wu et al. [42]	Training programs, enhanced PPE; DNA damage and oxidative stress focus	Technology transfer needs identified; biomonitoring program development

Table 3. Geographic Distribution and Protective Measures in Occupational Health Studies

Methodological Advances and Research Quality

The quality and sophistication of occupational health research in this field has improved substantially in recent years[9]. Early studies were often limited by small sample sizes, crude exposure assessment methods, and inadequate control for confounding factors[44]. In contrast, more recent investigations have employed sophisticated biomonitoring techniques, comprehensive health outcome assessment, and rigorous epidemiological methods[51][45]. However, significant methodological challenges still persist. The healthy worker effect remains a concern in many studies, potentially underestimating true health impacts[82][62]. Long latency periods for many health outcomes require extended follow-up periods that are difficult to maintain[80]. The complex mixture exposures typical of incineration environments complicate efforts to identify causal relationships with specific health outcomes[21].

Effectiveness of Protective Measures

The evidence base for protective measure effectiveness has grown substantially, providing clear guidance for evidence-based interventions[89]. Engineering controls, particularly advanced emission control systems, have demonstrated the greatest impact on exposure reduction[61][92][91]. Personal protective equipment can provide substantial additional protection when properly selected, fitted, and used consistently[90]. However, implementation of protective measures remains inconsistent across facilities and geographic regions. Economic considerations, technical complexity, and organizational factors all influence the adoption and effectiveness of protective measures[96][85]. Regulatory enforcement and technical assistance programs play crucial roles in ensuring widespread implementation of effective protection strategies[21].

Biomarker Development and Validation

Significant advances have been made in biomarker development for occupational exposure assessment[97][98]. Modern approaches employ comprehensive biomonitoring panels that provide detailed exposure characterization[93][12]. Relationships between environmental dust concentrations and serum levels have been established to validate biomarker approaches[48]. Recent developments include gene expression profiling and molecular biomarkers that may provide early indicators of exposure-related effects[51][77]. These advances enable more sensitive detection of occupational health impacts and better characterization of dose-response relationships.

Research Gaps and Future Priorities

Several critical research gaps persist despite decades of investigation[99]. Long-term health outcomes, particularly cancer risks, require continued follow-up of exposed cohorts with adequate statistical power[81][80]. The health effects of emerging contaminants need systematic investigation using modern toxicological and epidemiological approaches[86][85]. Mechanistic research has provided important insights into pathways of toxicity[100][76], but translation of these findings into practical prevention strategies remains limited. Biomarker development for emerging contaminants and early health effects requires continued investment and validation[51]. Intervention research represents a particularly important gap, with limited rigorous evaluation of protective measure effectiveness under real-world conditions[89]. Randomized controlled trials of specific interventions, while challenging in occupational settings, could provide stronger evidence for prevention strategies.

Implications for Global Waste Management Policy

The occupational health evidence has important implications for global waste management policy[1]. The reported health risks support arguments for waste reduction and recycling as preferable alternatives to incineration where technically and economically feasible[101][102]. However, where incineration is necessary, the evidence clearly demonstrates that modern emission control technologies and worker protection programs can substantially reduce health risks[57][37]. The global nature of waste trade and technology transfer creates opportunities for international cooperation in promoting occupational

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health protection[30]. Harmonized standards and technical assistance programs could help ensure that all workers, regardless of geographic location, receive adequate protection.

Limitations of Current Evidence

Several limitations affect the interpretation and application of the occupational health evidence[103]. Publication bias may have influenced the literature, with negative studies less likely to be published. The heterogeneity of facility types, waste compositions, and exposure scenarios limits generalizability of findings across different settings[9]. The observational nature of most studies limits causal inference, particularly for health outcomes with multiple potential causes[21]. Confounding by smoking, socioeconomic factors, and other occupational exposures remains a concern in many studies[66]. The relatively small size of the exposed population has limited statistical power for rare health outcomes[104][44].

Conclusion

The current review shows that waste incinerator workers face complex occupational health challenges that have evolved substantially with technological and regulatory developments[9][103][16]. While modern emission control technologies and worker protection measures have achieved significant reductions in exposure levels and health risks[37][57], complete elimination of occupational hazards has not been achieved[39][43].

Key Findings

Several key findings emerge from this comprehensive analysis:

1. *Substantial exposure reductions have been achieved:* Modern facilities typically show 80-90% lower exposure levels compared to early installations[50][55], reflecting the effectiveness of advanced emission control technologies and improved work practices[7].
2. *Health risks persist despite technological advances:* Even in modern facilities, workers show elevated exposure levels and increased health risks compared to background populations[14][17] indicating the need for continued vigilance and protection measures.
3. *Respiratory effects remain the most consistent health outcome:* Across all time periods and facility types, respiratory symptoms and pulmonary function changes represent the most consistently

reported health effects[3][66][65][67], with prevalence rates typically 2-3 times higher than in unexposed populations.

4. *Cancer risks appear to be declining:* Studies of workers in modern facilities suggest lower cancer risks compared to historical cohorts[81][62][37], although long latency periods require continued surveillance to confirm this trend.
5. *Emerging contaminants pose new challenges:* The increasing presence of brominated flame retardants, PFAS, and e-waste components in municipal waste streams creates new exposure scenarios[86][85][42] that are not adequately addressed by current protection measures.
6. *Geographic disparities in protection are substantial:* Workers in developing countries face exposure levels and health risks comparable to those reported in developed countries 20-30 years ago[32][39], highlighting global health equity concerns.

Implications for Practice

The evidence supports several key recommendations for protecting waste incinerator workers' health:

Engineering Controls: Advanced emission control technologies including fabric filters, activated carbon injection, and selective catalytic reduction should be standard at all facilities[92]. Enclosed ash handling systems and improved ventilation in work areas provide additional protection[61]. *Personal Protection:* Comprehensive PPE programs including respiratory protection, chemical-resistant gloves, and protective clothing are essential, particularly for high-risk activities[89][90]. Fit testing, training, and compliance monitoring are crucial for effectiveness[91]. *Health Surveillance:* Regular medical monitoring including respiratory function testing, biomarker assessment, and targeted health examinations enables early detection of exposure-related effects and guides intervention strategies[45][12]. *Training and Education:* Comprehensive worker education programs covering exposure risks, protective measures, and emergency procedures are fundamental for effective risk management[96]. *Regulatory Oversight:* Strict occupational exposure limits, regular workplace inspections, and enforcement of protection requirements provide essential frameworks for worker protection[58].

Research Priorities

Several research priorities emerge from this analysis: 1) *Long-term Health Studies:* Continued follow-up of exposed worker cohorts is essential for understanding cancer risks and other long-term health outcomes[35][36], particularly for workers in modern facilities with lower exposure levels[38]. 2) *Emerging Contaminants:* Systematic investigation of health effects from brominated flame retardants, PFAS, and other emerging pollutants requires priority attention using modern analytical and epidemiological methods[88][52]. 3) *Intervention Effectiveness:* Rigorous evaluation of protective measure effectiveness under real-world conditions could optimize prevention strategies and resource allocation[89]. 4) *Mechanistic Research:* Continued investigation of exposure pathways and biological mechanisms could identify new biomarkers and therapeutic targets for protecting worker health[51][78]. 5) *Global Surveillance:* International coordination of occupational health surveillance could improve understanding of geographic variations in exposure and health outcomes while promoting best practices[94][31].

Final Perspective

The waste incineration industry plays an essential role in global waste management, and this role is likely to expand as waste generation continues to grow worldwide[1]. The occupational health evidence demonstrates that this essential function can be performed with acceptable risks to worker health, provided that appropriate technological and regulatory frameworks are implemented and maintained[12][14]. The evolution of occupational health knowledge in this field provides a model for addressing emerging occupational health challenges in other industries. The combination of technological innovation, regulatory development, scientific research, and international cooperation that has driven improvements in waste incinerator worker protection offers lessons applicable to other complex occupational health challenges[9].

However, the persistence of significant health risks, particularly in developing countries and older facilities[39], remarks the ongoing need for vigilance, investment, and commitment to worker protection. The fundamental principle that essential industrial activities should not compromise worker health remains as relevant today, as it was when the first occupational health studies of waste incinerator workers were conducted some decades ago[4]. As waste streams continue to evolve, so too must the approaches to protect those who manage them, ensuring that occupational health keeps pace with both technological advancement and emerging environmental challenges[105][106][62].

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Glossary of Technical Terms

PCDD/Fs (Polychlorinated dibenzo-*p*-dioxins and dibenzofurans): A group of persistent organic pollutants formed during combustion processes. Highly toxic compounds that bioaccumulate in fatty tissues. Exposure is measured in toxic equivalents (TEQ) to account for varying toxicity of different congeners. **PFAS** (Per- and Polyfluoroalkyl Substances): A large family of synthetic fluorinated compounds used in numerous consumer and industrial products. Known as "forever chemicals" due to their environmental persistence. Health concerns include endocrine disruption and potential carcinogenicity. **BFRs** (Brominated Flame Retardants): Chemicals containing bromine used to reduce flammability in consumer products and electronics. Include polybrominated diphenyl ethers (PBDEs) among and other compounds. Health concerns include neurotoxicity and endocrine disruption. **WHO-TEQ (**World Health Organization Toxic Equivalents): A standardized method for expressing the toxicity of dioxin-like compounds, accounting for the varying potency of different congeners relative to the most toxic form (2,3,7,8-TCDD). **PAHs** (Polycyclic Aromatic Hydrocarbons): A group of organic compounds formed during incomplete combustion of organic materials. Many PAHs are known (or suspected) carcinogens. **E-waste** (Electronic Waste): Discarded electrical and electronic equipment containing complex mixtures of metals, plastics, and flame retardants. Increasingly present in municipal waste streams and poses unique incineration challenges.

Statements and Declarations

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