The health impacts of waste incineration: a systematic review

Peter W. Tait,[1,2] James Brew,[1] Angelina Che,[1] Adam Costanzo,[1] Andrew Danyluk,[1] Meg Davis,[1] Ahmed Khalaf,[1] Kathryn McMahon,[1] Alastair Watson,[1] Kirsten Rowcliff,[1] Devin Bowles[1,3]

Abstract

Introduction: Waste incineration is increasingly used to reduce waste volume and produce electricity. Several incinerators have recently been proposed in Australia and community groups are concerned about health impacts. An overview of the evidence on health effects has been needed.

Method: A systematic review of English language literature for waste incinerators and health using PRISMA methodology.

Results: A range of adverse health effects were identified, including significant associations with some neoplasia, congenital anomalies, infant deaths and miscarriage, but not for other diseases. Ingestion was the dominant exposure pathway for the public. Newer incinerator technologies may reduce exposure.

Discussion: Despite these findings, diverse chemicals, poor study methodologies and inconsistent reporting of incinerator technology specifications precludes firmer conclusions about safety.

Conclusion: Older incinerator technology and infrequent maintenance schedules have been strongly linked with adverse health effects. More recent incinerators have fewer reported ill effects, perhaps because of inadequate time for adverse effects to emerge. A precautionary approach is required. Waste minimisation is essential.

Implications for public health: Public health practitioners can offer clearer advice about adverse health effects from incinerators. We suggest improved research design and methods to make future studies more robust and comparable. We offer ideas for better policy and regulation.

Key words: waste, health, cancer, incineration, toxin

Waste management encompasses the avoidance, reduction, collection, transport, storing and disposal of waste products from municipal, health and industrial sources. Current disposal strategies include recycling, landfill and incineration.[1,2]

Waste management is of growing concern for communities globally and in Australia, with alternatives to traditional landfill increasingly being employed. Waste incinerators provide one alternative for reducing pressure on landfill. Modern incinerators are also designed to generate electricity, which increases their appeal to policymakers.[3–5]

Waste incinerator systems have traditionally been associated with emission of toxic pollutants, impacting human and environmental health. The Stockholm Convention provides international guidance on the safe management of persistent organic pollutants (POPs). The objective of the Convention is to minimise or prevent human exposure to POPs. It incorporates a precautionary and manufacturer/user pays approach. The guidelines cover waste incineration because this is a potential source of POPs, including dioxin-like compounds. Waste reduction is a key recomendation.[6]

Newer waste incinerator technologies are claimed to run more cleanly and with less environmental impact. Nevertheless, pollutants are still produced, with upgraded facilities requiring regular service to maintain emission levels.

Despite technological advancements, local and global health impacts from waste incinerators remain a concern for communities where they are being built. Adverse health outcomes in populations near waste incinerators, including cancers and reproductive dysfunction, have been demonstrated in primary studies.[7–12] Unfortunately, precise evaluation of the health impact of waste incinerators can be difficult due to confounding factors, including pollution from industries, automobiles and agriculture chemicals, latency for carcinogenicity, subacute and delayed reproductive/intergenerational effects, mobility of populations and other factors.

This systematic review aims to identify the health effects on human populations living near waste incinerators to inform the public and guide policymakers, and to define appropriate criteria for approving current and future waste incinerator proposals. We reviewed primary studies investigating levels of known pollutants in human and environmental samples as well as the health effects associated with waste incineration pollutants.

1. Australian National University Medical School, Australian Capital Territory
2. Public Health Association of Australia, Australian Capital Territory
3. Council of Academic Public Health Institutions Australasia, Australian Capital Territory
Correspondence to: Dr Peter Tait, Public Health Association of Australia, Canberra, Australian Capital Territory; e-mail: aspetert@bigpond.com
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Methods

Study inclusion criteria

This systematic review was conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.[13] We included peer-reviewed primary literature addressing health effects of waste incineration. Studies had to focus on the impacts of waste incineration on health risk and/or health outcomes. Papers had to be in English and accessible online and could not be protocols.

Search criteria

Relevant papers were found through a search of the PubMed database from 1 January 2002 through 31 December 2017, using the MeSH term 'waste management' AND keyword search terms 'incineration' AND 'health'. We did not search 'waste to energy' because incineration more generally was our primary focus. To keep the volume of literature manageable within time limits, and to harvest more recent and therefore up-to-date and relevant studies, we set the 15-year time horizon. A similar search on the Science Direct database did not yield any additional papers. The reference lists of captured systematic reviews were examined for further papers that met the inclusion criteria.

Study eligibility

Paper eligibility was evaluated independently against the criteria by two researchers using the abstracts. Disagreements were resolved by a third assessor. Eligibility was re-assessed when the full manuscript was read. The broader research team decided exclusions by majority decision.

Data extraction

Papers were randomly assigned to six group members to extract the following data from each manuscript: the study design; methods; country of study; incinerator properties; local and global health outcomes; bias; and main results. Study design was categorised as either randomised-controlled trial, cross-sectional, case-control, cohort, case study, case series, simulation or ecological. Local health outcomes were considered as those that affected populations living or working within the vicinity of waste incineration facilities; whereas, global health outcomes (primarily health impacts of global warming due to waste incineration) were considered for more distant populations.

We further classified papers according to impacts on health risks or health outcomes. Health risks were subclassified by assessment method as either external (measurements of air, soil, water, food, etc) or internal (measurements of serum, urine, breast milk, hair, or direct effects on cells and/or DNA). Health outcomes were further subclassified as neoplasia, reproductive health and other. Many papers examined both health risks and outcomes; they were included in multiple groups. Each paper was evaluated for its assessment of bias.

As a quality control measure, a separate reviewer examined 20% of papers to assess concordance between the different data-extraction teams.

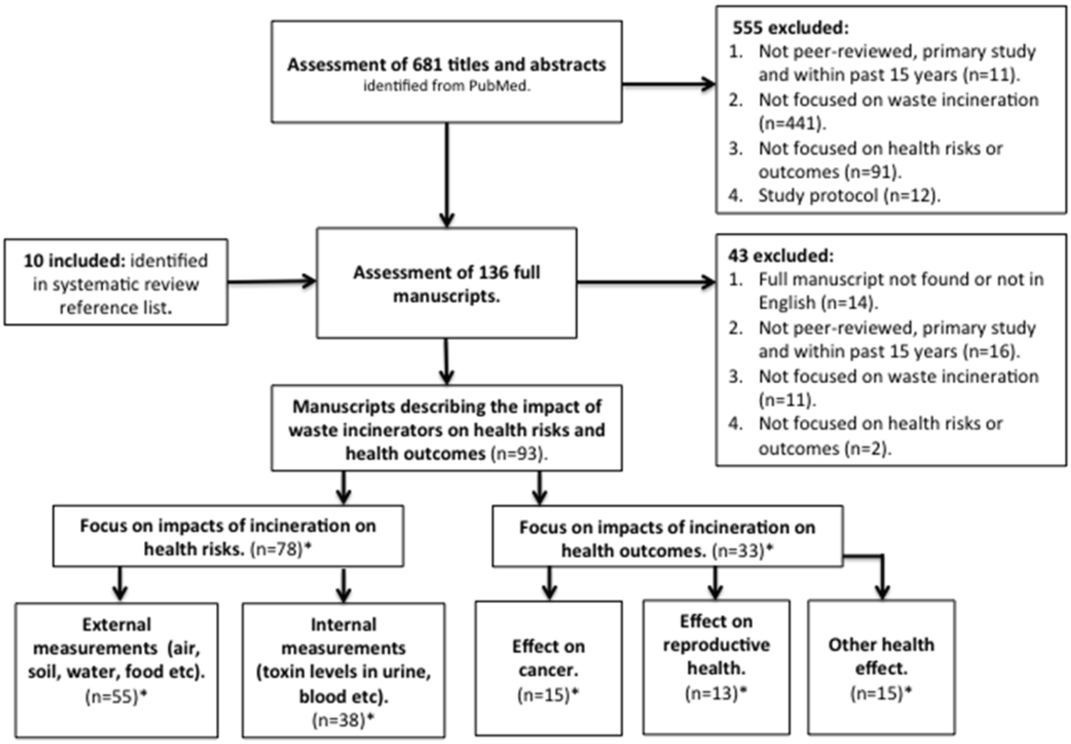
Grade of evidence

Each paper was graded according to the National Health and Medical Research Council (NHMRC) guidelines: A (excellent) to D (poor).[14]

Results and discussion

The identification of 93 manuscripts meeting criteria is detailed in Figure 1. Details are provided in the Supplementary File: Data Table. Most papers were graded low on NHMRC criteria; the highest grade awarded was C (satisfactory), see Supplementary File. The study designs reviewed included 19 cohort (prospective and retrospective) and case-control investigations. Overall methodological quality was satisfactory (five

Figure 1: PRISMA diagram for the identification of peer-reviewed papers included in the review.



Note:
** Some manuscripts fit into multiple subgroup classifications.*

studies) to poor (14 studies), with the absence of randomisation and blinding as the chief impediments to obtaining higher grade. This is not a major limitation given the necessarily observational nature of the studies.

The five studies assessed as satisfactory were based on results gained from a generalisable study population; they reported findings with valuable clinical impact (odds-ratios and risk-ratios) and considered bias.[15-19]

The 74 lower-grade studies comprised cross-sectional (42), case-study (2), longitudinal (4), ecological (2), simulation (19), observational (1) and life-cycle analysis (4) studies. Absence of control groups and no analysis of bias were the chief impediments to obtaining a higher grade.

Concordance between different members of the data-extraction team was satisfactory at greater than 80%.

Overall, we identified 61 (66%) papers that demonstrated a significant adverse outcome in relation to waste incineration. Of these, 34 (37%) showed exposure to elevated levels of known pollutants, nine (10%) identified an increased risk of developing some neoplasia, nine (10%) found a correlation with adverse reproductive outcomes, and nine (10%) found a link to other diseases such as hypertension or reduced lung function. No papers investigated the global health effects of waste incineration.

Note that, while occupational exposure is mentioned in some cases, this is usually as a comparator to local resident exposure. In addition, exposed workers can be sentinels for effects that can be sought in the wider public.

Exposure risk – external measurements

Fifty-five papers analysed external measures of exposure. Most were cross-sectional, ecological or simulation types. A common format for studies involved measuring plant stack emissions (or samples taken at different distances from stacks) and modelling exposure based on a mixture of demographics, food consumption patterns and weather. This was usually based on US EPA modelling guidelines[20] to calculate exposure by inhalation, dermal contact, soil contact and ingestion. Exposure levels were acceptable (within local regulations) in 23 papers, while 25 found that the exposure could lead to adverse outcomes and seven made neither judgement. Eleven of the 55 papers found that newer incinerator technologies led to reduced exposure, either by pre- and post-analysis following incinerator upgrades, or via comparison of multiple incinerators of varying ages.

Dietary ingestion was consistently the largest route for toxic emission exposure. Six papers concluded this explicitly,[21-26] while other studies attributed the majority of exposure burden to food ingestion, based on pre-existing research.

Few studies acknowledged other potential sources of pollutants, despite every incinerator facility operating near other polluters: transport, factories or refineries. Details concerning incinerator design were omitted in 23 studies, precluding comparison of the efficacy of different stack emission cleaning systems and making these results difficult to interpret.

Exposure risk – internal measurements

Thirty-six papers[15,22,27-60] investigated exposure to waste incinerator emissions by measurement of body substances. Upon review, five were found to have been misclassified and were excluded from the analysis. This heterogeneous group of 31 papers measured exposure in a variety of ways, including cell studies and measurements of organic and non-organic substances in body fluids and hair. Substances studied included dioxins, furans, heavy metals and polycyclic aromatic hydrocarbons (PAH). Given the diversity of substances and methods of measurement, the variability in results is unsurprising.

Findings from internal measurements

Increased levels of substances were measured in nearby residents and workers (who may also be nearby residents).

Cell function and damage

Five papers performed cell studies, encompassing studies on cell viability, immune cell activation, markers of mutation and markers of oxidative damage. Of these, three reported significant findings. Cao et al.[56] exposed human A459 cells to particulate matter from incinerator atmospheric samples and found increased production of reactive oxygen species and reduced cell viability. Oh et al.[38] compared blood samples from 31 waste incineration workers and 84 control subjects and found significantly increased T-cell activation in incineration workers. Leem et al.[52] measured urinary markers of oxidative stress in 13 workers and 16 residents near a municipal waste incinerator and compared these to samples from 10 residents near an industrial waste incinerator; residents near the industrial incinerator had significantly higher markers than those near the municipal incinerator. The lack of control group and small sample size limit the utility of this analysis in making conclusions regarding the safety of municipal waste incinerators.

Dioxins and furans (PCDD/Fs)

Nineteen papers assessed effects of exposure to concentrations of polychlorinated dibenzodioxins (PCDDs/dioxins) and polychlorinated dibenzofurans (PCDFs/furans) in the human body. Of these, five reported significant results. Yamamoto et al.[39] measured PCDD/PCDF blood concentrations in 16 incineration workers over an eight-year period after the closure of the incinerator in 1997, finding PCDD levels 4.7 times higher and PCDF levels 21.2 times higher compared to the local farming population. Although this result looks alarming, the age of the incinerator studied may limit its applicability to the modern context. The impact of incinerator age was also demonstrated by Reis et al.,[36] who measured dioxin concentrations in breast milk and found significantly higher concentration in mothers exposed to the older, compared to the modern, incinerator. Leem et al.[52] found significantly higher blood dioxin concentration in 10 residents near an industrial incinerator compared to 29 workers and residents near a municipal incinerator but did not compare these results to controls without exposure to incinerators.

Chen, Su and Lee[22] investigated the relationship between food consumption and blood dioxin concentration in 1,709 residents near 19 incinerators in Spain, finding significantly higher blood dioxins in those consuming locally grown food compared to those who did not ($p<0.0001$). Similar results were found in Ranzi et al.[59] and Cordier et al.[24] Most other studies used residents who lived further away from an incinerator as a control group compared to residents who lived closer as the exposure group; distance was assumed to be a proxy for exposure. The dominance of food ingestion among exposure pathways potentially confounds these results, as the assumed 'controls', who in many cases only lived kilometres away from the 'exposed', may have eaten the same-sourced foods. Further meteorological conditions may carry toxins longer distances.[61] Distance from residence to incinerator should therefore not be regarded a legitimate proxy for exposure, given the likelihood of confounding factors leading to an underestimation of effect.

Heavy metals

Ten papers assessed concentrations of heavy metals, of which five reported statistically significant results. Deng et al.[34] measured blood mercury concentrations in 35 incinerator workers in China and 269 exposed local residents with 143 control subjects. After controlling for confounders including food consumption habits, they found significantly higher mercury levels in the incinerator workers and exposed group compared to controls (median levels 1.02 mg/L, 0.81 mg/L, 0.70 mg/L, respectively; $p<0.05$). The raised levels in both the workers and exposed residents corroborates the potential problem of using local residents, who might consume the same food sources, as controls. Reis et al.[55] measured lead concentration in hair and blood from 497 children living in Spain, finding that while significantly higher levels of lead were found in the exposed compared to the control group, lead levels were relatively low across the study participants, although the lead action level used was higher than in other countries. This result is consistent with Reis et al.,[35] who also found a significant but mild increase in maternal and newborn blood lead, although the concentrations were all below the established action level. Chao and Hwang[58] found significantly higher concentrations of urinary and blood arsenic in workers compared to age- and sex-matched residents. A modifying factor was workers' use of activated carbon facemasks and gloves during working hours. Ranzi et al.[59] found a dose-response trend for urinary and serum heavy metals and PAH in their study of 65 subjects living near or working in an incinerator and with 103 controls.

Polycyclic aromatic hydrocarbons

Four papers assessed the concentrations of PAH, of which three reported statistically significant results. Oh et al.[38] found urinary PAH metabolites were 15 and 3.5 times higher in incineration workers compared to the controls ($p<0.05$). This result was consistent with a later study performed by Ranzi et al.,[59] which found significantly higher urinary PAH in the exposure group compared to controls. Incinerator technology seems to influence the exposure to PAH, as demonstrated by a study by Ichiba et al.,[32] which found significantly higher urinary PAH in workers at an older incinerator compared to a more modern one.

Waste incinerator exposure and neoplasia risk

Several studies showed that local residents may be exposed to carcinogenic levels of pollutants from waste incinerator emissions. However, the utility of these studies in guiding incinerator design is limited, with many studies omitting crucial information regarding the type of incinerator design, specific criteria to define local residents, and details outlining the analysis of bias and confounders.

Non-Hodgkin lymphoma

Non-Hodgkin lymphoma has been associated with waste incinerator exposure. Floret et al.[15] studied waste incinerator exposure (since 1971 in two locations and 1976 in another) and non-Hodgkin lymphoma cases in local residents compared to a control population. After accounting for confounders, a relationship was established between dioxin exposure and non-Hodgkin lymphoma; exposure levels greater than 0.0004 pg/m^3 resulted in an odds ratio of 2.3 (95%CI 1.4–3.8). Viel et al.[62] identified a low-risk ratio of 1.120 (95%CI 1.002–1.251) for non-Hodgkin lymphoma in local residents, although only in females; the period studied was 1972–85.

Soft tissue sarcoma

Soft tissue sarcomas have also been linked to exposure to waste incinerator emissions. Zambon et al.[63] revealed an increased risk of sarcoma related to exposure to a large variety of incinerators and waste streams. The only exposure associated with a significant odds ratio was for levels greater than 6 fg/m^3 dioxin species (OR 3.27; 95%CI 1.35–7.93). This studied peak exposure over the period 1972–86. Comba et al.[16] studied local residents of an incinerator in Mantua, Italy, and found an alarming odds ratio of 31.4 (95%CI 5.6–176.1) for sarcoma in residents within 2 km of the incinerator. Notably, Mantua was recognised for its unregulated and toxic waste streams through the period 1974–91.

Bowel cancer

Ranzi et al.,[64] using a cohort study, demonstrated bowel cancer risk increased in residents near a waste incinerator. After controlling for confounders, analysis revealed significant bowel cancer risk ratios for mortality in men (RR 2.1; 95%CI 1.1–4.4), and incidence in women (RR 2.0; 95%CI 1.3–3.06). Parodi et al.[65] conducted a cross-sectional study linking lung cancer deaths and heavy metal concentrations in soil utilising a dispersion model. Results included increased risk for women with high (RR 2.14; 95%CI 1.09–4.20) and low (RR 1.54; 95%CI 1.01–2.36) exposure. However, the region studied had multiple pollution sources not factored into the analysis, reducing validity of the results.

Other cancers

Federico et al.[8] performed an ecological study across multiple incinerators and a large population of exposed local residents. The study correlated stomach, gallbladder, lung and pleural cancer mortality with distance to incinerators. All cancer risks were above unity but only slightly, with an overall cancer mortality risk ratio of 1.06 (95%CI 1.04–1.09; $p<0.0001$). Viel et al.[17] found women aged over 60 years in the highest exposure bracket were actually less likely to be diagnosed with invasive breast cancer (OR 0.31; 95%CI 0.08–0.89); however, this study had limited technical incinerator detail.

Several studies showed no association of cancer risk to waste incinerator exposure. In Japan, Fukuda et al.[9] reported that cancers in residents near waste incinerators had no significant relationship to dioxin exposure across a large variety of exposure periods. Additionally, Domingo et al.[66] performed a case study that sampled and then modelled air and soil pollutant levels in the vicinity of waste incinerators. They concluded that carcinogenic risk from waste incinerators was similar to background levels in any industrial or urban area, suggesting that, while waste incineration is at most not worse than traditional industrial and urban pollution sources, this level of exposure would add to the historical baseline level. Finally, Garcia-Perez et al.[18] performed an ecological study of two incinerators and were unable to identify a spatial trend between cancer incidence and proximity to incinerator. These studies suggest that relationships between proximity and effects may be neither direct nor linear.

Overall, results relating to neoplasia were mixed. This is unsurprising given that many use proximity to the incinerator as the independent variable, despite the limitations of this approach described earlier. Further, most papers omitted pertinent details on incinerator design, and several statistically significant results were inconsequential as they approached unity. Nevertheless, the seriousness of neoplasia diagnoses warrants a precautionary approach to incinerator exposure. Further, earlier periods of exposure have a stronger link with cancers such as non-Hodgkin lymphoma and sarcoma.

Reproductive outcomes

Eleven eligible studies[11,12,24,38,49,67-72] examined the effects of waste incinerator exposure on a wide range of reproductive outcomes. Nine of these found significant adverse effects, including preterm delivery, reduced sperm quantity and quality, congenital anomalies, infant deaths, and miscarriage.

Preterm delivery

All three studies examining preterm delivery demonstrated an association between exposure to pollutants from incinerators and preterm and earlier gestational age at birth. Santoro et al.[12] performed a cross-sectional study of 3,153 births from 2001 to 2010 near an incinerator in Italy and found that, after adjusting for confounders, there was an increased risk of preterm birth in primiparous women (OR 2.18; 95%CI 1.05–4.53; p=0.033). This result was consistent with a larger study of 21,157 births conducted by Candela et al.,[67] which found that increased exposure to particulate matter from eight incinerators in Italy was significantly associated with an increase in preterm delivery (OR 1.30; 95%CI 1.08–1.57; p<0.001), as well as for very preterm babies (OR 1.44; 95%CI 1.11–1.85; p<0.001). Lin, Li and Mao[49] found a small reduction in gestational age at birth in exposed groups. Although statistically significant, the effect size was tiny (0.09 weeks). Overall, these results suggest an association between exposure to incinerator pollutants and preterm birth, but further research is required to rule out potential confounders relating to location and time frame used in the first two studies.

Sperm analysis

Oh et al.[38] conducted a cross-sectional comparison of sperm count and motility for six waste incineration workers and eight controls and found that the sperm count was significantly lower in waste incineration workers compared to the control subjects (p=0.05). The authors also found that the incineration workers had more DNA damage in their spermatozoa compared to the controls (mean olive tail moment 1.40 vs. 1.26, p<0.001). The small sample size and lack of adjustment for confounding factors limit the utility and generalisability of this study.

Congenital anomalies

Five studies investigated congenital anomalies, with four finding a significant association between exposure to pollutants from incinerators and increased risk of congenital anomalies. These significant results included lethal heart and neural tube defects, facial clefts and renal tract defects, as well as infant death with congenital anomalies.

A retrospective cohort study by Dummer, Dickinson and Parker[70] used population registries to collect data on 244,758 births in the UK between 1956 and 1993 and found a significantly increased risk of lethal heart defects (OR 1.12; 95%CI 1.03–1.22; p<0.01) and lethal neural tube defects (OR 1.12; 95%CI 1.07–1.28; p<0.01) among births in closer proximity to incinerators. Although the large size of this study increases its value, the study period might limit its applicability to the modern context.

More recent studies have confirmed an association between incinerators and congenital anomalies. A retrospective cohort study by Tango et al.[69] found a dose-response association for infant deaths from congenital malformations for births in Japan between 1997 and 1998 in areas near incinerators with higher compared to lower soil dioxin levels (p=0.047). Cordier et al.[68] conducted a retrospective cohort study in France using data from 1988–97 and found increased frequency of facial clefts (RR 1.30; 95%CI 1.06–1.59) and renal dysplasia (RR 1.55; 95%CI 1.10–1.20) in the incinerator-exposed communities. Additionally, a dose-response association of increased risk of obstructive uropathies was observed between the low, medium and high exposure groups (RR 1, 1.38 and 1.93 respectively). Cordier et al.[24] followed this up with a case-control study in which cases of renal/urinary tract anomalies were matched with controls and assessed for exposure to incinerators. This study controlled extensively for environmental, social and individual confounders and found significantly increased risk of renal/urinary tract birth defects linked to higher exposure from incinerator-produced atmospheric dioxins (OR 2.84, 95%CI 1.32–6.09) and dioxin deposits (OR 2.95; 95%CI 1.47–5.92). The effect size and more rigorous study design provides stronger evidence for an association between exposure to incinerators and renal/urinary tract congenital anomalies.

Miscarriage

Four studies looked at miscarriage and stillbirth; however, only one found a significant association with exposure to incinerator emissions. This cross-sectional study by Candela et al.[11] used population registries and hospital records and found increased risk of hospitalisation for miscarriage among women without previous miscarriages with a higher compared to lower exposure based on incinerator dispersion modelling (OR 1.29; 95%CI 0.97–1.72; p=0.042). They also modelled alternative exposure sources. The use of hospital records did not capture the women who were not surgically managed for their miscarriage and the strength of the association is limited due to the odds ratio crossing unity. Moreover, since the study design was based on EPA dispersion modelling, not real-world emission sampling, the result may underestimate the true effect size.

Dioxins interfere with several biological processes that are key to embryonic and foetal development and are causally linked to poor birth outcomes. The associations found here can be partially explained through a teratogenic pathway. Dioxins, particulate matter and heavy metals, all emitted by incinerators, are known teratogens,[73,74] demonstrating plausibility for a causal link between waste incinerators and congenital anomalies and miscarriage. The association between incinerators and preterm birth, however, demonstrates that dioxin teratogenicity does not account for all adverse reproductive outcomes associated with waste incinerators. Other possible links include effects of dioxins on placental development and function[75] as well as endocrine signalling.[76,77]

Overall, the literature demonstrates increased risk of adverse reproductive outcomes associated with exposure to waste incinerators, in particular preterm birth and congenital anomalies. Conversely, no significant association appeared for sex ratio,[12,67,69] birth weight,[12,49,67,69] small for gestational age[12,67] and neonatal death.[69,70] Nevertheless, the outcomes for which a significant association was found represent severe and potentially tragic health and personal implications, which warrant careful consideration and planning to mitigate risks from proposed waste incinerator facilities in Australia.

Other diseases

Seventeen eligible studies examined waste incinerator impacts on a range of other health outcomes. Adverse health effects, including on overall mortality and burden of disease, cardiovascular, respiratory, metabolic, dermatologic, childhood developmental delay and mental health (see Supplementary File) were absent or insignificant.

Overall mortality and burden of disease

Epidemiological studies in Japan[9] and Italy[64] showed no increased all-cause mortality associated with living in proximity to incinerators and increased exposure to dioxins, oxides of nitrogen or heavy metal emissions from waste incinerator facilities. Galise et al.[78] modelled a 0.12% increase in overall deaths in the studied region attributable to fine particle (PM10, <10μm in diameter) exposure, while Li et al.[79] concluded waste-to-energy incineration had the lowest non-cancer risks under normal operation but carried the highest cancer risk in comparison to other waste management strategies. Kim et al.[80] calculated the burden of disease (measured in years of life lost and disability-adjusted life years) in populations close to waste incinerators in Korea to be small.

Cardiovascular mortality and morbidity

Fukuda et al.[9] demonstrated no evidence of increased ischemic heart disease-related mortality in surrounding populations with adjustment for socioeconomic status, while Ranzi et al.[64] inferred no clear trends for increased cardiovascular or ischemic heart disease mortality in those exposed to heavy metals or living near incinerators regardless of adjustment for co-exposure with oxides of nitrogen.

Galise et al.[78] modelling attributed a 0.19% (95%CI 0.11–0.28) increase in cardiovascular mortality and 0.06% (95%CI 0.00–0.12) of heart disease-related hospital admissions to potential exposure to 40μg/m^3 of PM10 incinerator emissions; these are very low increases in risk ratios. Contrastingly, Chen et al.[81] demonstrated a significant association between serum dioxin levels and the occurrence of hypertension (OR 5.58; 95%CI 1.63–19.62; p=0.007) among populations living close to incinerators.

Respiratory mortality and lung function impairment

Galise et al.[78] demonstrated a 0.27% respiratory mortality and 0.12% hospital admission rate to PM10 incinerator emissions (95%CI 0.11–0.42, 0.04–0.23, respectively), while Ranzi et al.[64] ruled out any increase in mortality or hospital admissions due to lung diseases and COPD among residents in proximity to incinerators compared with a reference population.

Studies by Hours et al.[82] and Charbotel et al.[19] both demonstrated significant impairment of lung function among incinerator workers. However, only Hours et al. were able to demonstrate a correlation between lung function impairment and occupational pollutant exposure. Hazucha et al.[83] were not able to demonstrate a similar link between paired resident and control communities.

Metabolic syndrome and endocrine disorder

Chen et al.[81] investigated serum dioxin levels and biochemical abnormalities in residents living close to incinerators. The study demonstrated elevated blood glucose levels (p=0.003), blood urea/nitrogen (p=0.003) and uric acid (p=0.019) with no significant association to diabetes mellites (p=0.07) and gout. In addition, there was no evidence for any correlation between dioxin exposure and anaemia, gallstones, goitres or hyperthyroidism.

Similarly, Yamamoto et al.[84] found that blood dioxin levels among incinerator workers did not differ from the general Japanese population. Increased $HbA1_C$ levels were shown to correlate with blood dioxin level among incinerator workers; however, the prevalence of diabetes among incinerator workers was similar to that in the general population.

Yoshida et al.[30] found a positive correlation between serum oestradiol (E3) and dioxin levels, but no difference in the oestrone (E1) urinary metabolite after adjustment for age, BMI, smoking and alcohol consumption. The authors of this paper did not comment on the potential health outcomes associated with elevated levels of oestrogen; hence the finding is of uncertain clinical consequence.

Dermatological symptoms

A study by Chen et al.[81] showed that exposure to dioxins was protective against dermal allergies (OR 0.29; 95%CI 0.09–0.91; p=0.034) in populations living near incinerators. Conversely, Oh et al.[82] showed significantly more subjectively and objectively reported skin lesions compared with controls with a dose-dependent relationship (moderate occupational exposure: OR 4.85; 95%CI 2.04–11.51 and high occupational exposure: OR 5.03; 95%CI 2.00–12.67). No relationship between distance of Japanese schools from waste incinerators and incidence of atopic dermatitis or allergic rhinitis was demonstrated in students.[85]

Childhood wellbeing

Lung et al.[86] identified an increased risk of mild-to-moderate developmental delay at ages six months and 36 months in Taiwanese children living near incinerators compared to control populations with adjustment for socioeconomic status. Miyake et al.[85] analysed residential proximity to a waste incinerator and parent-reported illness and symptoms in elementary school children. Living in proximity to a municipal waste incinerator was independently associated with increased prevalence of wheeze (adjusted OR 1.08; 95%CI 1.01–1.15), headache (adjusted OR 1.05; 95%CI 1.00–1.11), stomach ache (adjusted OR 1.06; 95%CI 1.01–1.11) and fatigue (adjusted OR 1.12; 95%CI 1.08–1.17).

Mental health

Only one study investigated stress levels secondary to the fear of occupational exposure to dioxins among municipal solid waste incinerator workers, which was lower than the general stress experienced by office workers.[87]

In vitro and in vivo oxidative stress

Chronic oxidative stress has been implicated in ischemic heart disease, carcinogenesis and respiratory disease. Yoshida et al.[88] investigated the duration of employment of incinerator workers in Japan and levels of serum and urine markers of oxidative stress. The marker of systemic oxidative stress did not correlate with job duration, while the level of urinary 8-hydroxy-2′-deoxyguanosine, a marker of oxidative DNA damage, had a positive correlation with length of employment, after adjustment for alcohol consumption, smoking and age (p<0.05). However, the relation to disease risk is uncertain.

Overall, negative health outcomes were demonstrated by a reduction in measured lung function parameters in incinerator workers. Out of three studies looking at the effects of incineration-associated pollution on cardiovascular morbidity and mortality, only one showed a significant association between serum dioxin levels and hypertension. As such, the contribution of incinerators to cardiovascular disease risk is undetermined. The impact of incinerator pollution on metabolic function was demonstrated by an elevation of blood glucose levels, without an increased risk of diabetes mellitus. Regarding dermatologic symptoms, conflicting results were demonstrated among incinerator workers, paediatric and general populations in both self-reported and objectively measured lesions. Therefore, no firm conclusions can be drawn.

Limitations

Definitive studies on the link between waste incineration and health are difficult to conduct due to the diversity of pollutants emitted, and the complex nature of disease aetiology and pathophysiology. This problem is exacerbated by multiple exposure routes, experimental design limitations, unpredictable and indeterminable weather patterns, confluent and unmeasured alternative sources of pollution, unspecified incinerator design elements and cleaning systems used, unknown maintenance schedules and unrecorded content of waste streams. Proximity of incinerators to the local populace, number of years lived near incinerator, water and food sources and consumption patterns introduce a third set of uncontrolled confounders.

Bias and study design affected robustness of results. Exposure misclassification was a recurring, undefined weakness. Control groups were often poorly matched to experimental groups. Not all studies reported confounders; for example: migration trends, places of occupation and other factors (smoking, alcohol, diet, education, occupation, time spent inside/outside incinerator among workers, age, sex, household condition, urban/rural status, overall health status, breast feeding status and route of toxin contact [dermal, inhalation, ingestion]) were variably reported. Where reported, none of these had significant effect on health outcome. Use of distance as a proxy for exposure, lack of control groups, small sample sizes and an inability to establish a causal relationship weakened ability to draw firm conclusions. Given the diversity of exposure and dispersal routes, it is not clear how important socioeconomic status would be as a confounder.

The diversity found in the literature suggests the true neoplasia risk remains obscure, and evidence implies exposure to incinerators increases risk of cellular damage due to intake of dioxins, furans, metals and polycyclic aromatic hydrocarbons. The variation in results between studies measuring different exposures and different risks suggests that at least some waste incinerators are likely to increase the risk of at least some types of neoplasia.

One limitation of any review like this is the possibility of data dredging. If widespread, it would create the appearance of a causal link between waste incineration and ill health. The risk may be low in this study because there is a presumptive link between waste incineration and ill health. This means that a study not finding a connection would be approximately as notable as one finding a connection.

Despite ingestion being considered the primary exposure route in the literature that specifically examines this variable, most studies only considered inhalation and dermal exposure to pollutants in their study design.

Incinerator design specifics were often omitted from papers and detail about waste streams and stack emission treatments were inconsistent, making comparisons of different design elements and systematic comparison of results difficult.

Waste incinerator designs have changed over the past decades and papers comparing emissions from an incinerator before and after upgrade mostly showed significant reductions in measured pollutant levels. Older incinerator technologies featured in most studies, therefore subsequent improvements in incinerator technologies may mean these results will not accurately represent the health consequences of exposure to current incinerators. However, since many health effects require cumulative exposure and may take many years to manifest, it will be difficult to measure any improved safety from modern incinerator designs for decades.

Finally, compared to other energy sources, the financial costs of waste to energy are high.[89] Further building reliance on maintaining a waste stream for supply of material counteracts the imperative to reduce waste.

Implications for public health

Based on this review, we provide researchers with suggestions for design and methods that will make future studies more robust and their results better comparable. Additionally, public health practitioners can offer the public, policy makers and regulators clearer advice about incinerator safety.

Future studies

This review has revealed substantial gaps and inconsistencies. These preclude clear assessment of which incinerator-related variables are important for health impacts. Future studies should:

- include information on the waste, including content and volume, incinerator technical characteristics such as stack height, type of combustion chamber, stack cleaning mechanisms and maintenance schedules, and the types and quantities of emissions;
- where possible, analyse or control for three exposure pathways: ingestion, inhalation and dermal exposure. The possible lack of correlation between distance from the incinerator and the intensity of all three of the pathways should guide study design and interpretation of results;
- report a range of variables potentially related to health effects;
- control for or account for absence of control for likely confounders; and
- determine whether those living downwind of incinerators are at risk.

Finally, further research is needed to compare different incinerator designs, and incineration with other methods of waste management. This will allow more rigorous and meaningful comparisons between waste disposal options.

Policy and regulation

- Since there has been insufficient time for health effects of newer technology to emerge, a precautionary approach to licensing and monitoring incinerators must continue.
- As a condition of applying for a licence to build waste incinerators, independent third-party conducted baseline population studies and long-term surveillance cohort studies be mandated to measure the longitudinal and emerging effects of the incinerator's presence on the local community and the environment.
- Health and safety standards for workers should be enshrined in law and should include regular health checks and exposure monitoring.
- In countries that have ratified the Stockholm Convention, incinerators should be designed to meet the Convention guidelines.
- Facility upgrades and regular maintenance schedules for incinerators must be adhered to.
- New incinerators should be located away from areas of food production.
- Food grown near an incinerator should be avoided.

Conclusion

This is the first systematic review that links the literature on exposure assessments (internal and external toxin measurements) to health outcomes. While we recognise that all studies discovered had limitations (only five reached NHMRC criterion C), this review permits assessment of incinerator safety.

This review shows contamination of food and ingestion of pollutants is a significant risk pathway for both nearby and distant residents. While occupationally exposed groups have been shown in primary studies to most likely suffer adverse effects, they are a relatively smaller population than all residents in the vicinity of incinerators. Workers may be considered a sentinel population for adverse effects. Incinerator workers are probably also local residents so also subject to exposures outside the workplace. Both local residents ingesting food grown in close proximity to incinerators, as well as more distant populations consuming food transported from areas near an incinerator, are open to exposure. Because most studies in this review examined only a small subset of potential exposure and disease pathways, together with the low quality, it is likely that our review has 'under-discovered' the full health-effects picture.

This systematic review highlights significant risks associated with waste incineration as a form of waste management. Many older incinerators were linked with neoplasia, reproductive issues and other diseases. While the results were not consistent across the literature, based on a precautionary principle there is insufficient evidence to conclude that any incinerator is safe. There is some suggestion that newer incinerator technologies with robust maintenance schedules may be less harmful, but diseases from exposures tend to manifest only after many years of cumulative exposure, so it is premature to conclude that these newer technologies improve safety.

Incineration for waste management, including waste-to-energy options, is likely to remain an alternative that governments will consider. However, the financial and ecological costs of waste to energy are comparably high. Building reliance on a waste stream for energy counters the need to reduce waste overall. This review suggests that incineration is not without problems and so it is an option that needs to be pursued carefully with close monitoring. Local community groups have a basis for legitimate concern and so siting of incineration facilities needs to take these concerns into account. Early transparent consultation with communities about these facilities is essential.

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Supporting Information

Additional supporting information may be found in the online version of this article:

Supplementary File 1: Data table - Summary of primary peer-reviewed manuscripts looking at the effects of waste incineration on health risks and health outcomes published from 2002 to 2017.