

**From:** [Stacy Hampton](#)  
**To:** [Coffin Butte Landfill Appeals](#)  
**Subject:** Fwd: Deny Coffin Butte Expansion Permit  
**Date:** Sunday, October 19, 2025 8:51:48 PM  
**Attachments:** [PMC10010672.pdf](#)  
[PMC9399006.pdf](#)  
[PMC1637771.pdf](#)  
[PMC2805622.pdf](#)  
[PMID39977375.pdf](#)  
[PMC2649222.pdf](#)  
[PMC11709132.pdf](#)

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From: **Stacy Hampton** <[stacyrhampton@gmail.com](mailto:stacyrhampton@gmail.com)>  
Date: Sun, Oct 19, 2025 at 8:38 PM  
Subject: Deny Coffin Butte Expansion Permit  
To: <[landfillappeals@benton.county](mailto:landfillappeals@benton.county)>

Dear Commissioners,

As a Benton County resident, the risks of providing garbage services to many counties in two states are just not worthwhile given the known long-term risks to air/soil/water quality. Additionally, I am highly concerned about emerging risks related to landfill fires and Benton County residents' increased exposure to microplastics as only 7 percent of the garbage is reported to originate in Benton County. I am also saddened by the higher rate of oncologic conditions reported by people I've met who live within a 5 mile radius of the Coffin Butte Landfill. As described in the attached research articles, any attempts by Republic Services to remediate these effects are inadequate due to the close proximity of inhabitants and the surrounding environment. I urge you to **deny Republic Services' expansion appeal** based on substantial peer-reviewed scientific evidence demonstrating serious environmental and health risks:

#### **Environmental Contamination Risks:**

- Landfill leachate inevitably contaminates groundwater with toxic heavy metals exceeding EPA drinking water standards (PMC10010672)
- Air emissions include methane, VOCs, and particulate matter causing respiratory disease and cancer risks (PMC9399006)
- Soil contamination spreads beyond site boundaries, affecting agricultural and residential areas

#### **Public Health Impacts:**

- Epidemiological studies consistently show increased rates of birth defects, low birth weight, occupational risks, and specific cancers in populations near landfills (PMC1637771, PMC2805622, PMC11709132). Additionally, class action lawsuits and

scientific evidence support previous legal precedents related to massive liability exposure for landfill operators. (PMC 2649222)

- Children face disproportionate risks from heavy metal exposure through contaminated air, water, and soil. (PMID 39977375)

### **Economic Liability:**

- If environmental contamination occurs, Benton County could face **Superfund designation** with cleanup costs averaging tens of millions in remediation per EPA estimates.
- The county would bear long-term liability for environmental remediation, potentially costing taxpayers millions. In particular, scientific consensus is building in regard to the harms of microplastics. Both Benton County and Republic Services will likely face long-term risks related to retroactive liability associated with microplastics and other toxins.

**Summary:** The documented risks to air/water/soil quality, combined with potential multi-million dollar litigation risk due to cleanup or health effects, far outweigh any short-term economic benefits. Protecting Benton County residents' health and financial interests requires denying the Coffin Butte expansion.

Sincerely,  
Anastasia Hampton

Physical Address: 1539 NW Forestgreen Corvallis OR 97330

Email: [stacyrhampton@gmail.com](mailto:stacyrhampton@gmail.com)

**References available through PubMed.gov using the PMC citation numbers provided above.**

### **Attachments:**

#### **PMC10010672 - Groundwater Contamination and Heavy Metal Exposure**

Landfills cause groundwater contamination through leachate containing heavy metals such as lead, cadmium, nickel, and manganese, with studies showing that groundwater near landfill sites often exceeds safety standards for heavy metals, making it unsafe for drinking and agricultural use. Exposure to heavy metals from contaminated groundwater can lead to kidney damage, liver failure, neurological problems, reproductive effects, and increased cancer risk, with metals also accumulating in crops irrigated with contaminated water, further increasing human exposure through the food chain.

#### **PMC9399006 - Landfill Health Effects and Environmental Contamination**

Landfills contribute to environmental contamination through the release of hazardous substances (heavy metals, VOCs, POPs, pathogenic waste) into soil, water, and air, leading to adverse health effects including acute poisoning, cancer, respiratory issues, and developmental problems, especially in children. Air emissions contribute to smog, acid rain, and respiratory

diseases, while leachate contamination causes long-term ecological damage and bioaccumulation in the food chain, with studies linking exposure to neurological diseases, cancers, and antibiotic-resistant infections.

#### **PMC1637771 - Epidemiological Studies on Population Health Near Landfills**

Epidemiological studies indicate that populations living near hazardous waste landfill sites may have increased risks of low birth weight, birth defects, and certain cancers, though methodological limitations and lack of direct exposure measurement make it difficult to quantify these risks. Self-reported symptoms such as fatigue, sleepiness, and headaches are consistently more prevalent among residents near landfills, but quantification of health risks is challenging due to insufficient exposure data and difficulty establishing effects from low-level environmental exposures.

#### **PMC2805622 - Birth Defects and Cancer Near Landfills**

Living near landfills is associated with a small but statistically significant increased risk of birth defects, low birth weight, and certain cancers (prostate, stomach, liver, lung in men; stomach and cervix uteri in women), with odds ratios for congenital anomalies ranging from 1.01 to 1.41. However, these findings are limited by lack of direct exposure measurements, short latency periods, and incomplete data, making it difficult to confirm a causal relationship, though the risk is higher near hazardous waste landfills compared to non-hazardous sites.

#### **PMC2649222 - Love Canal Landfill Public Health Effects**

Describes landmark class action litigation due to landfill health effects related to birth defects, chromosomal damage (33% vs 1% in general population), nervous disorders, and cancers.

#### **PMID 39977375- Large elevations in airborne lead levels in urban fire**

Elevated atmospheric lead levels create toxic air contamination that accumulates in human tissues and affects nearly every organ system, with children being especially vulnerable to neurodevelopmental effects.

#### **PMC11709132- Occupational Exposure at Electronics Waste Facility**

Details risks and complications of mercury exposure for workers at an electronics waste facility and the worker safety liabilities that occurred.

# Health Effects of Residence Near Hazardous Waste Landfill Sites: A Review of Epidemiologic Literature

Martine Vrijheid

Environmental Epidemiology Unit, Department of Public Health and Policy, London School of Hygiene and Tropical Medicine, London, United Kingdom

This review evaluates current epidemiologic literature on health effects in relation to residence near landfill sites. Increases in risk of adverse health effects (low birth weight, birth defects, certain types of cancers) have been reported near individual landfill sites and in some multisite studies, and although biases and confounding factors cannot be excluded as explanations for these findings, they may indicate real risks associated with residence near certain landfill sites. A general weakness in the reviewed studies is the lack of direct exposure measurement. An increased prevalence of self-reported health symptoms such as fatigue, sleepiness, and headaches among residents near waste sites has consistently been reported in more than 10 of the reviewed papers. It is difficult to conclude whether these symptoms are an effect of direct toxicologic action of chemicals present in waste sites, an effect of stress and fears related to the waste site, or an effect of reporting bias. Although a substantial number of studies have been conducted, risks to health from landfill sites are hard to quantify. There is insufficient exposure information and effects of low-level environmental exposure in the general population are by their nature difficult to establish. More interdisciplinary research can improve levels of knowledge on risks to human health of waste disposal in landfill sites. Research needs include epidemiologic and toxicologic studies on individual chemicals and chemical mixtures, well-designed single- and multisite landfill studies, development of biomarkers, and research on risk perception and sociologic determinants of ill health. **Key words:** epidemiology, hazardous waste, health effects, landfill, residence, review. — *Environ Health Perspect* 108(suppl 1):101–112 (2000).

<http://ehpnet1.niehs.nih.gov/docs/2000/suppl-1/101-112vrijheid/abstract.html>

The disposal of wastes in landfill sites has increasingly caused concern about possible adverse health effects for populations living nearby, particularly in relation to those sites where hazardous waste is dumped. Studies on the health effects of landfill sites have been carried out mainly in North America and existing reviews focus entirely on this literature (1,2). Recent publications of large studies both in and outside North America warrant an update of evidence presented in previous reviews. Up-to-date knowledge about epidemiologic evidence for potential human health effects of landfill sites is important for those deciding on regulation of sites, their siting and remediation, and for those whose task it is to respond to concerns from the public in a satisfactory way.

We intend to present a critical discussion of all major epidemiologic studies published since 1980 on health effects related to residence near landfill sites in North America, Europe, and elsewhere. Special attention is paid to recent studies and studies outside the United States that have not been included in previous reviews.

## Methods

Throughout this review the term landfill is used for any controlled or uncontrolled disposal of waste to land. Relevant papers were found through computerized literature searches on MEDLINE (MEDLINE

Database, National Library of Medicine, Bethesda, MD) ([www.biomednet.com](http://www.biomednet.com)) and BIDS Databases, Joint Information Systems Committee, University of Bath, Bath, UK ([www.bids.ac.uk](http://www.bids.ac.uk)) from 1980 through to 1998 using keywords “landfill” and “hazardous waste site.” In addition, articles were traced through references listed in previous reviews. All papers found in this manner that studied health effects in residents near waste landfill sites and that were published in journals available through the British Library and libraries of the University of London were included in this review. A few papers referred to in previous reviews could not be traced because they were published in local journals in the United States. Published reports of recent studies that have not yet appeared in peer-reviewed journals have been included in the review. A few abstracts of European studies have been included, although full research papers of these studies have not been published because they reflect growing concerns about landfill in Europe. A total of 50 papers, reports, and abstracts are reviewed in this article. Investigations of the health risks to those employed in the handling, transport, clean-up, or maintenance of substances at landfill sites are very scarce and have not been included in this review. Many chemicals or groups of chemicals potentially present in landfill sites, including organic

solvents, polychlorinated biphenyls (PCBs), and heavy metals, have shown adverse effects on human health or in animal experiments. A discussion of findings from either epidemiologic or toxicologic research on health effects related to specific chemicals is beyond the scope of this review.

## Epidemiologic Studies on Health Effects of Landfill Sites

The majority of studies evaluating possible health effects in human populations living near landfill sites investigate communities near one specific waste disposal site (single-site studies), frequently in response to concerns from the public about reported contamination from the site or reported clusters of disease. A small number of studies have addressed the risks of living near waste sites, independent of whether the sites caused concern, by a priori specifying a number of sites for study. These will be referred to as multisite studies. Single- and multisite studies have different methodologic problems and are therefore discussed separately in this paper. Most individual studies are discussed in detail in this article. Where appropriate due to common methodologic issues (e.g., in studies of self-reported health outcomes and clusters of disease) or due to a common landfill site of concern (e.g., in the Love Canal studies and Santa Clara County studies), less emphasis was put on individual studies and more on common issues. Studies included in the review are summarized in Table 1 (single-site studies) and Table 2 (multisite studies). Discussion of individual single- and multisite studies is preceded by a discussion of issues common to the interpretation of all landfill studies.

Address correspondence to M. Vrijheid, Environmental Epidemiology Unit, London School of Hygiene and Tropical Medicine, Keppel Street, WC1E 7HT London, UK. Telephone: 44 171 927 2415. Fax: 44 171 580 4524. E-mail: [m.vrijheid@lshtm.ac.uk](mailto:m.vrijheid@lshtm.ac.uk)

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**Table 1.** Single-site studies.

| Ref. | Study design            | Study subjects                                                                                 | Exposure measure                                                                                | Health outcomes studied                                                                                                                  | Reported findings                                                                                                                                    |
|------|-------------------------|------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| (7)  | Geographical comparison | Love Canal census tract; comparison: New York State                                            | Residence in Love Canal census tract                                                            | Cancer: liver, lymphomas, leukemia, other organ sites                                                                                    | No increased incidence                                                                                                                               |
| (8)  | Cross-sectional         | 46 exposed residents; comparison: residents in adjacent census tract                           | Residence in houses where chemicals were detected                                               | SCEs and CAs                                                                                                                             | No difference in frequency of chromosome changes                                                                                                     |
| (9)  | Cross-sectional         | 523 Love Canal children; 440 control children                                                  | Proximity to site; at least 5 months' residence in Love Canal area                              | Self-reported health problems: seizures, learning problems, hyperactivity, eye irritation, skin rashes, abdominal pain, and incontinence | Increased prevalence of all symptoms                                                                                                                 |
| (10) | Cross-sectional         | 428 Love Canal children; 493 control children                                                  | Born in Love Canal and more than 75% of life in Love Canal                                      | Children's stature, weight, weight for stature                                                                                           | Shorter stature for Love Canal children. No difference in weight                                                                                     |
| (11) | Retrospective follow-up | 174 births near site; 443 live births in rest of Love Canal area; all births in New York State | Residence in Love Canal area                                                                    | LBW                                                                                                                                      | Higher percentage of LBW in exposed area; excess in period of active dumping                                                                         |
| (12) | Retrospective follow-up | 239 exposed children; 707 unexposed                                                            | Residence in Love Canal area during pregnancy                                                   | LBW, birth defects                                                                                                                       | 3-fold risk of LBW (homeowners only); increased risk for birth defects (homeowners and renters)                                                      |
| (26) | Retrospective follow-up | 2,092 births in proximate area; 6,840 births in control area                                   | Residence at birth in area closest to landfill                                                  | Average birth weight, LBW, preterm birth                                                                                                 | Significantly lower average birth weight, higher proportion of LBW and prematurity during the time of heaviest pollution                             |
| (14) | Retrospective follow-up | 25,216 births                                                                                  | Residence in census tract, proximate zone, and frequency of odor complaints                     | LBW, fetal mortality, infant mortality, prematurity                                                                                      | No difference over entire study period; moderate decrease in birth weight in high odor complaint zone in period of highest exposure                  |
| (27) | Case-control            | 7,977 LBW cases; 7,856 control births                                                          | Residence in areas adjacent to landfill and level of estimated exposure to landfill gas         | LBW, very LBW, preterm birth, small for gestational age                                                                                  | Excess in LBW and small for gestational age births; no excess in very LBW or preterm birth                                                           |
| (21) | Geographical comparison | Residents of Montreal Island                                                                   | Residence in areas adjacent to landfill and level of estimated exposure to landfill gas         | Cancers of 17 organ sites for men; 20 organ sites for women.                                                                             | Increase in incidence of stomach, liver, lung and prostate cancer for men, stomach and cervix-uteri cancer for women.                                |
| (15) | Cross-sectional         | 51 residents of exposed village incl. 11 children and 52 control persons                       | Residence in exposed village                                                                    | SCEs                                                                                                                                     | Higher frequency of SCEs in exposed population, particularly in children                                                                             |
| (28) | Cross-sectional         | 47 children from exposed village; 45 unexposed children                                        | Residence in exposed village and time of exposure                                               | Chromosomal changes                                                                                                                      | Chromosome damage frequency returned to background levels after site remediation                                                                     |
| (29) | Geographical comparison | Cancer deaths and birth defects compared to Pennsylvania and U.S.                              | Residence in counties surrounding waste site, incl. Clinton county, PA                          | Bladder cancer and cancers of other organ sites; birth defects                                                                           | Increase in bladder cancer deaths in Clinton; increase in number of other cancers in Clinton and 3 surrounding counties; no excess in birth defects. |
| (16) | Cross-sectional         | 179 long-term exposed residents; 151 residents in comparison areas                             | Residence in area near waste site                                                               | 14 self-reported diseases; 15 self-reported symptoms                                                                                     | Increased prevalence of skin problems and sleepiness                                                                                                 |
| (17) | Cross-sectional         | 1,049 exposed; 948 unexposed residents                                                         | Residence in household close to site                                                            | 36 self-reported health problems                                                                                                         | Increased prevalence of minor respiratory symptoms (wheezing, cough, persistent cold), irregular heart beat, fatigue, bowel complaints               |
| (30) | Retrospective follow-up | 614 exposed households; 636 comparison households                                              | Residence within 750 m of edge of site: long-/short-term residence                              | Self-reported health problems                                                                                                            | Increased prevalence of mood disorders, narcotic symptoms, skin and respiratory disorders, eye problems, muscle weakness                             |
| (31) | Cross-sectional         | 403 exposed households; 203 comparison households                                              | Residence in proximate area                                                                     | 19 self-reported diseases, 23 symptoms; mortality, cancer incidence, LBW, birth defects, spontaneous abortions                           | Increase in majority of self-reported diseases and symptoms. No significant association for mortality, cancer morbidity, reproductive effects        |
| (32) | Cross-sectional         | 257 residents in exposed zones; 105 in comparison area                                         | Distance based zones: zone 1: < 300 m zone 2: 300–1,000 m                                       | Self-reported diseases and symptoms, miscarriages, stress levels                                                                         | Increased reporting of majority of symptoms, miscarriages, stress                                                                                    |
| (18) | Follow-up survey        | 57 high-, 66 low-, 70 unexposed residents                                                      | Exposure zones based on odor zones                                                              | 22 self-reported health problems                                                                                                         | 2-fold increase in 64% of reported symptoms                                                                                                          |
| (33) | Cross-sectional         | 321 high-exposed persons; 351 persons with low/minimal exposure                                | Cumulative exposure index based on distance from sites and amount of chemicals present at sites | 29 self-reported health problems                                                                                                         | Excess in reporting of 11 of 29 symptoms: mainly neurologic symptoms                                                                                 |

(Continued)

Table 1. Continued.

| Ref. | Study design                  | Study subjects                                                                   | Exposure measure                                                                                    | Health outcomes studied                                                                                                                 | Reported findings                                                                                                                                                                                           |
|------|-------------------------------|----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (34) | Cross-sectional               | 456 exposed residents; 481 comparison persons                                    | Residence near site                                                                                 | 14 self-reported health problems                                                                                                        | Increased reporting of 11 of 14 symptoms.                                                                                                                                                                   |
| (19) | Retrospective follow-up       | 694 residents                                                                    | Individual exposure index based on concentration of pollutants and daily activity of study subjects | Amount of prescribed medication for selected diseases (respiratory, ophthalmologic, dermatologic, gastrointestinal, neurologic)         | No relationship between individual exposure index and drug consumption                                                                                                                                      |
| (20) | Case-control                  | 432 cases; 384 controls                                                          | Individual exposure index based on concentration of pollutants and daily activity of study subjects | Dermatologic, respiratory, eye, gastrointestinal diseases, psychologic disorders and other conditions                                   | Relationship between exposure level and existing cases of respiratory and psychologic conditions                                                                                                            |
| (38) | Geographical comparison       | Three counties adjacent to waste dump compared to whole region                   | Communities near dump; distance of community to dump                                                | Leukemia, multiple myeloma, malignant lymphoma                                                                                          | Excess in leukemia incidence                                                                                                                                                                                |
| (39) | Geographical comparison       | Ward surrounding landfill compared to whole region                               | Residence in landfill ward, surrounding wards, area downwind from landfill                          | All childhood cancers                                                                                                                   | No excess of childhood cancer                                                                                                                                                                               |
| (40) | Geographical comparison       | 5 wards near landfill compared to 22 wards elsewhere                             | Wards near landfill                                                                                 | Mortality rates, hospital admissions for asthma, cancer, and other conditions, spontaneous abortions, birth defects, drug prescriptions | No consistent differences in mortality rates, hospital admissions, spontaneous abortions. Excess in birth defects before and after start of the landfill. Increase in prescriptions for certain medications |
| (41) | Geographical comparison       | Cancer rates in 8 counties in Illinois compared to national rates                | Residence in town with contaminated wells                                                           | Bladder cancer                                                                                                                          | Excess in bladder cancer in town with contaminated wells                                                                                                                                                    |
| (44) | Geographical comparison       | Woburn cancer rates compared to national rates                                   | Residence in Woburn                                                                                 | Childhood leukemia                                                                                                                      | More than 2-fold excess in childhood leukemia                                                                                                                                                               |
| (45) | Case-control                  | 20 leukemia cases; 164 control children                                          | Exposure index based on fraction of water supply in household from contaminated wells               | Childhood leukemia                                                                                                                      | Significant association with exposure index                                                                                                                                                                 |
| (45) | Retrospective follow-up       | 4,396 pregnancies; 5,018 children under 18                                       | Exposure index based on fraction of water supply in household from contaminated wells               | Childhood disorders; adverse pregnancy outcomes: spontaneous abortions, perinatal death, LBW, birth defects                             | Increase in eye/ear anomalies, CNS/chromosomal/cleft anomalies; perinatal deaths; kidney/urinary tract disorders, lung/respiratory disorders                                                                |
| (46) | Cross-sectional               | 28 family members of leukemia cases; 30 healthy controls                         | Being a family member of a Woburn leukemia case                                                     | Immunologic abnormalities, medical examination                                                                                          | Immunologic abnormalities in family members                                                                                                                                                                 |
| (47) | Retrospective follow-up       | Births in exposed census tracts compared to births in the entire county          | Residence in census tract served by contaminated water supply                                       | Congenital heart defects                                                                                                                | 2-fold excess in cardiac anomalies                                                                                                                                                                          |
| (48) | Retrospective follow-up       | Pregnancies in exposed census tract; pregnancies in unexposed census tract       | Residence in census tract served by contaminated water supply                                       | Spontaneous abortions, birth defects, LBW                                                                                               | Increase in spontaneous abortions and birth defects; no excess in LBW                                                                                                                                       |
| (49) | Retrospective follow-up       | Pregnancies in 2 exposed census tracts; pregnancies in 2 unexposed census tracts | Residence in 2 census tracts served by contaminated water supply                                    | Spontaneous abortions, birth defects, LBW                                                                                               | No excess in spontaneous abortions or malformations in new exposed study area                                                                                                                               |
| (50) | Retrospective follow-up       | Pregnancies in 2 exposed census tracts                                           | % water in census tract from contaminated well; estimated concentration of solvents                 | Spontaneous abortions, birth defects                                                                                                    | No relation between abortion or malformation rate and estimated exposure                                                                                                                                    |
| (51) | Case-control                  | 145 cases with cardiac malformations; 176 nonmalformed control births            | Mother's consumption of home tap water                                                              | Congenital heart defects                                                                                                                | Elevated risk for consumption of more than 4 glasses of tap water compared to none                                                                                                                          |
| (52) | Retrospective follow-up       | 349 pregnancies in 1 exposed and 1 unexposed census tract                        | Mother's consumption of home tap water                                                              | Spontaneous abortions, birth defects                                                                                                    | Spontaneous abortions: significant trend with number of glasses tap water per day. Birth defects: no trend                                                                                                  |
| (53) | Retrospective follow-up       | 1,016 pregnancies in exposed and unexposed areas                                 | Mother's consumption of home tap water                                                              | Spontaneous abortions, birth defects, LBW                                                                                               | Spontaneous abortions: 7-fold risk for any versus no tap water. Birth defects: nonsignificant increase. No association with LBW                                                                             |
| (13) | Cross-sectional and follow-up | 49 exposed residents; 57 unexposed residents                                     | Use of contaminated well water                                                                      | Liver function                                                                                                                          | Abnormalities in liver function in exposed residents. Returned to normal 2 months later.                                                                                                                    |
| (54) | Cross-sectional               | 676 exposed residents; 778 unexposed residents                                   | Residence in high-exposure area based on ground-water flow                                          | Self-reported disease: cancer, liver disease, respiratory illness, skin disease, seizures                                               | Statistically significant increase in respiratory disease and seizures, not significant after accounting for smoking                                                                                        |
| (55) | Cross-sectional               | 65 exposed residents; 66 residents from control households                       | Residence in households with contaminated well water                                                | 15 self-reported health symptoms; 14 self-reported diseases                                                                             | Increased reporting of eye irritation, diarrhea, sleepiness.                                                                                                                                                |

Abbreviations: CAs, chromosomal aberrations; CNS, central nervous system; LBW, low birth weight; SCEs, sister chromatid exchanges.

**Table 2.** Multisite studies.

| Ref  | Study design            | Study sites                                                   | Study subjects                                                                                    | Exposure measure                                                                                      | Health outcomes studied                                                          | Reported findings                                                                                                                                                                          |
|------|-------------------------|---------------------------------------------------------------|---------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (56) | Geographical comparison | 593 NPL waste sites in U.S.                                   | 339 counties with waste site, more than 3,000 without                                             | County with site                                                                                      | Cancer mortality                                                                 | Increased rates of cancer of the lung, bladder, stomach, and rectum                                                                                                                        |
| (57) | Case-control            | 12 sites in New York State                                    | 339 deceased lung-cancer cases; 676 deceased controls                                             | Residence in census tract with site; duration of residence                                            | Lung cancer                                                                      | No association                                                                                                                                                                             |
| (58) | Case-control            | 38 sites with likely landfill gas migration in New York State | 9,020 cancer cases; 9,169 deceased controls                                                       | Residence within 250 ft                                                                               | Cancer of liver, lung, bladder, kidney and brain; non-Hodgkin lymphoma, leukemia | Excess of female bladder cancer and female leukemia                                                                                                                                        |
| (59) | Case-control            | 300 sites in 1,072 census tracts in California                | 5,046 birth defects cases and 28,085 control births. 1,904,000 births for birth weight analysis   | Residence in census tract with site and potential for human exposure                                  | Birth defects, LBW                                                               | 1.5-fold increase in risk of heart defects. Other malformations and birth weight not associated                                                                                            |
| (60) | Case-control            | 1,281 NPL sites in U.S.                                       | 17,407 births                                                                                     | Residence within 1 mile                                                                               | Birth weight, birth defects, fetal deaths, infant deaths                         | No association between adverse pregnancy outcomes and living near a NPL site                                                                                                               |
| (61) | Case-control            | 590 waste sites in New York State                             | 9,313 live births with birth defects; 17,802 normal control births                                | Residence within 1 mile and hazard score of site                                                      | Birth defects                                                                    | Increased risk for all malformations (12%), integument system, nervous system, musculoskeletal. Indications for dose-response relation with exposure risk                                  |
| (62) | Case-control            | 643 waste sites in New York State                             | 473 cases with central nervous system defects; 3,305 musculoskeletal cases; 12,436 control births | Ratings of exposure probability within 1 mile of each site                                            | Central nervous system defects and musculoskeletal defects                       | No association between two types of and proximity to waste sites                                                                                                                           |
| (64) | Case-control            | 317 waste sites in New York State                             | 259 cases of end-stage renal disease and 259 controls                                             | Residence within 1 mile, exposure probability; years of residence within 1 mile                       | End-stage renal disease                                                          | Nonstatistically significant increase in risk of renal disease for ever living within 1 mile, having lived within 1 mile for more than 12 years, and a medium/high probability of exposure |
| (65) | Case-control            | 105 NPL and 659 non-NPL sites in California                   | 507 neural tube defects, 517 controls; 210 heart defects, 439 oral clefts, and 455 controls       | Census tracts: no site, non-NPL site, NPL site; residence within 1 mile and residence within 1/4 mile | Birth defects: neural tube defects, heart defects, and oral clefts               | No increased risks relating to residence in census tract with site. Small, nonsignificant increase in risk of NTD and heart defects for living within 1/4 mile                             |
| (66) | Case-control            | 21 sites in 5 European countries                              | 1,089 cases with non-chromosomal birth defects; 2,366 control births                              | Residence within 3 km                                                                                 | Birth defects                                                                    | Increased risk for all malformations (33%), NTD, cardiac defects                                                                                                                           |

NTD, neural tube defect.

### Issues Common to the Interpretation of Landfill Studies

A general problem in epidemiologic studies of landfill sites, whether studying single or multiple sites, is that there is insufficient information regarding potential human exposures from landfill sites. Although landfill sites are numerous and widespread, very few have been evaluated with respect to both the types of chemicals they contain and the extent to which they may be releasing chemicals. Most such work has been conducted in the United States under the Superfund program (3). In other countries, information is largely lacking. Moreover, although chemicals have been found to migrate off site at a number of sites that have been thoroughly investigated (2), we know very little about the extent to which residents living near a site are exposed to these chemicals. A few studies that have attempted to measure certain chemicals in blood and urine of populations near waste sites have

generally not found increased levels of volatile organic compounds (VOCs) (4), mercury (5), or PCBs (6). Because knowledge of whether and to what extent substances from waste sites reach the human population is still largely lacking, and because resources are rarely available to carry out extensive exposure measurements or modeling, epidemiologic studies have based the assessment of exposure to landfills mainly on surrogate measures such as residence in an area close to a waste site or distance of residence from a waste site. The use of such surrogate, indirect exposure measurements can lead to misclassification of exposure which, if not different for diseased and nondiseased persons, will decrease the sensitivity of the study to find a true effect.

In addition to being hampered by insufficient exposure data, the study of landfill exposures is complicated by the fact that if residential populations are exposed to

chemicals from landfill sites, it will generally be to low doses of mixtures of chemicals over long periods of time. Associations with such low-level environmental exposures in the general population are by their nature hard to establish. Low-dose exposures are generally expected to generate small increases in relative risk that will be difficult to distinguish from noise effects introduced by confounding factors and biases.

In most of the landfill studies reviewed in this article, residents near waste sites are studied without knowledge of the exact route(s) of exposure to chemicals from the site. Migration of hazardous substances into groundwater is often an important environmental concern in relation to landfill sites, which may represent a public health problem, especially when a site is located near aquifers supplying public drinking water. However, in many situations the drinking water supply of residents near waste sites does not originate

from the local area. For people living in the vicinity of these sites, other routes of exposure may be of more concern. Landfill sites may be a source of airborne chemical contamination via the off-site migration of gases and via particles and chemicals adhered to dust, especially during the period of active operation of the site. Very little is known about the likelihood of air exposure from landfill sites through landfill gases or dust. At some of the sites described below, low levels of volatile organic chemicals have been detected in indoor air of homes near landfill sites (7–13), in outdoor air in areas surrounding sites (14–20) or in on-site landfill gas (21). Other possible routes of exposure include contamination of soil, ground, and surface water, which may lead to direct contact or pollution of indoor air in the case of evaporation of VOCs into basements of nearby houses. Contamination via the food chain may sometimes be of concern for nearby residents in the case of consumption of home-grown vegetables. Drinking water is a possible route of exposure only if water for domestic use is locally extracted. If this is the case, other domestic water uses (bathing, washing) may also lead to exposure via inhalation of evaporated VOCs and/or direct contact (13).

Some issues related to specific health outcomes should be noted in both single- and multisite studies. A general problem in studies of cancer incidence is the long latency period between exposure and clinical manifestation of the cancer. Studies may not always allow for a long enough latency period, which reduces their power to pick up long-term effects. Moreover, because of the long latency period, a considerable number of people may have migrated into or out of the exposed areas between time of exposure and time of diagnosis, which will lead to misclassification of exposures. Studies of chromosome changes (chromosome aberrations and sister chromatid exchanges) are undertaken with the assumption that such changes are related to the mechanisms underlying cancer and possibly birth defects. Chromosomal changes are studied as biomarkers of early response or effect of exposure to mutagenic and carcinogenic chemicals. Sorsa et al. (22) point out that theoretically it is reasonable to assume that chromosome damage is directly related to cancer etiology, but the number of agents clearly shown to induce such damage in humans is still limited. Increased frequencies of chromosome changes may indicate exposure to mutagens and carcinogens, but it is not clear at present how well they predict cancer risk. Low birth weight is thought to be relatively sensitive to effects of chemical exposures (23). It is also relatively easy to collect accurate information on birth weight from birth certificates. However, a large number of risk factors are

associated with low birth weight (including smoking, socioeconomic status, nutritional factors, parental height) (24), and these may act as confounding factors, giving biased estimates of association with residence close to a site. Birth defects have fewer established risk factors than other reproductive outcomes such as low birth weight, and studies of birth defects may therefore be less affected by confounding factors, although unknown risk factors could still play a confounding role. Also, birth defects represent an etiologically very heterogeneous set of conditions; analyses of the total malformation rate (all defects combined) have the advantage of larger numbers but may not be sensitive enough to pick up increases in risk of specific defects. The grouping of malformations into groups that are etiologically similar is difficult because of lack of knowledge on causes of specific defects. Grouping therefore always entails a compromise between large enough numbers and etiologic specificity.

### Single-Site Studies

The investigation of single landfill sites has been important as a response to community concerns; many of the single-site studies discussed below are prompted by public concerns, often under considerable political pressure. This means that they are prone to recall and reporting biases that may weaken the investigations and partly explain increases in reported health outcomes. Single-site studies have examined a vast range of possible health outcomes, often without a specific disease hypothesis being proposed a priori. Such “fishing expeditions” are thought to be of less scientific value than studies that start with a clear hypothesis (1). Including these fishing expeditions in evaluating the consistency of findings across multiple studies is important nevertheless when assessing evidence for health risks.

A less avoidable problem in single-site studies is that the size of populations living near waste sites generally is small and, especially when the outcome is a rare disease, this can seriously limit the statistical power of an investigation.

Single-site studies discussed in this section are grouped into those examining hard end points such as cancer and reproductive outcomes, those studying self-reported health outcomes and symptoms, those following up reported clusters of disease near landfill sites with geographic comparisons of disease rates, and those specifically investigating the contamination of well water used for drinking or other domestic uses in relation to health effects. These last studies were discussed separately to determine whether conclusions can be drawn about specific pathways of exposure.

**Studies of cancers, reproductive outcomes, and chromosomal damage.** Large quantities of toxic materials (residues from pesticide production) were dumped at the landfill of Love Canal, New York State, during the 1930s and 1940s, followed by the building of houses and a school on and around the landfill in the 1950s. By 1977 the site was leaking and chemicals were detected in neighborhood creeks, sewers, soil, and indoor air of houses. This led to one of the most widely known and publicized incidents of environmental pollution from landfill. Exposure of Love Canal residents, although not well understood, may have occurred via inhalation of volatile chemicals in home air or via direct contact with soil or surface water (10). The drinking water supply was not contaminated. Chemicals detected at Love Canal were primarily organic solvents, chlorinated hydrocarbons and acids, including benzene, vinyl chloride, PCBs, dioxin, toluene, trichloroethylene, and tetrachloroethylene. Several studies were conducted to detect whether Love Canal residents suffered adverse health effects.

Janerich et al. (7) compared cancer incidence for the Love Canal area with data for the entire state from 1955 to 1977 and found no increase in cancer rates at Love Canal for any organ site. This included leukemia, lymphoma, and liver cancer, which were thought to be the cancers most likely to result from exposures to the chemicals found at the site. The study is limited in that no information was available on confounding factors such as socioeconomic status and smoking. Subsequently, Heath et al. (8) compared the frequencies of chromosome changes (sister chromatid exchanges and chromosomal aberrations) in residents who lived in the first ring of houses adjacent to Love Canal in 1978 with those of control persons from socioeconomically similar census tracts. No differences in frequencies of chromosome damage were found. Chromosome changes were measured in 1981 and 1982, a few years after people were evacuated from the first ring of houses and therefore were no longer exposed. The authors point out that chromosome damage may be a reversible effect, which may explain the negative findings.

Infants and children have been the subject of other Love Canal studies. A cross-sectional study (9) reported an increased prevalence of seizures, learning problems, hyperactivity, eye irritation, skin rashes, abdominal pain, and incontinence in children living close to the Love Canal site compared to controls from other areas, as reported by the parents of the children. It has been noted in previous reviews (1,25) that this study was conducted in 1980, 2 years after the residents of Love Canal had become aware of the hazardous

waste problem, when media and public interest were high, and people were being evacuated. This makes it likely that the results were biased by differential reporting of health problems. However, a similar population of children (spending 75% or more of their childhood in the Love Canal area) had significantly shorter stature for their age than control children after allowing for factors such as birth weight, socioeconomic status, and parental height (10). Vianna and Polan (11) found an excess of low birth weights (less than 2500 g) during the period of active dumping (1940–1953) in areas of Love Canal where exposure had been highest. Rates of low birth weight between 1960 and 1978 after the site had been closed were comparable to those in upstate New York as a whole. It is not clear whether exposure from Love Canal was highest during the active dumping period or during the period after the site was closed, when the building of houses near the site increased and the landfill was leaking. A study by Goldman et al. (12) reported a 3-fold risk of low birth weight for children exposed during gestational life to the Love Canal area compared to that for control children born elsewhere from 1965 to 1978. Data were analyzed separately for homeowners and renters so that groups of similar socioeconomic status were compared, and after allowing for confounding factors, the risk of low birth weight was significantly increased for homeowners only. This finding is difficult to interpret because there are no strong reasons to believe that homeowners would be more susceptible than renters to the effects of toxic chemicals. In the same study an increased risk of birth defects was observed for both homeowners and renters. Information on birth defects relied mainly on reports from parents. Some recall bias can therefore be suspected, in particular for defects of lesser severity, but this is unlikely to account for the entire association found for major birth defects.

Berry and Bove (26) studied birth weight at the Lipari Landfill in New Jersey, a site for municipal and industrial waste. Leachate from the site migrated into nearby streams and a lake adjacent to a residential area. Inhalation of volatile chemicals emitted from the landfill and contaminated waters was thought to be the most important exposure pathway. The site closed in 1971 after complaints of residents, but the heaviest pollution was estimated to have occurred during the late 1960s to the mid-1970s. The study found a convincing increase in proportion of low birth weight babies (< 2500 g) and a lower average birth weight in the population living closest (within a radius of 1 km) to the landfill in the time period when potential for exposure was thought to be greatest

(1971–1975) compared to these factors in a control population. Although information on some confounding variables such as smoking, alcohol consumption, and socioeconomic status was not available, mothers in the exposed area were more highly educated and therefore appeared to be of higher socioeconomic status. One would expect higher birth weights in areas of higher socioeconomic status, so as the authors point out, confounding by socioeconomic status does not explain the lower birth weights found. In time periods before and after heavy dumping and off-site pollution, birth weights were higher in the area closer to the site than in the control area, which supports the hypothesis that pollution from the waste site may have been related to low birth weights in the community close to the site.

A range of reproductive effects including low birth weight was studied around the large BKK hazardous waste disposal site in Los Angeles County, California (14), after previous investigations of vital records found that trends in low birth weight and neonatal deaths corresponded closely with times and quantities of dumping at the landfill. Results for the whole study period showed no increase in adverse reproductive effects, but during the period of heaviest dumping, birth weights were significantly lower in exposed areas than in control areas using odor complaint frequency zones to classify exposure. All results were adjusted for education, income, and race. The decrease in mean birth weight found in the high-odor complaint zone was small (59 g) compared to that in the Lipari Landfill study (192 g) and was less than a third of birth-weight reductions caused by smoking during pregnancy (26). Odor complaint frequency zones corresponded better with vinyl chloride monitoring data and meteorology around the site than did census tract areas or distance-based (< 0.7 miles) exposure zones, and this was therefore thought to be the most accurate method for classifying exposure. Using census tract or distance-based exposure zones, smaller decreases in mean birth weight were found (35.2 g,  $p = 0.02$  and 20.4 g,  $p = 0.25$ , respectively).

Miron Quarry, a large (the third largest in North America) municipal solid waste site in Montreal, Quebec has prompted studies on both reproductive outcomes (low birth weight and preterm births) (27) and cancers (21). Gas from the site was the main environmental and health concern and a range of VOCs, including a number of recognized or suspected human carcinogens, had been detected in the gas. An excess of 20% in low birth weight was found among babies of mothers who were living in the high-exposure area adjacent to the landfill at the time of

delivery, taking account of confounding factors such as education and age of the mother. No excess was found in the low-exposure zone compared to a control area. Exposure zones were based on proximity to the site and accounted for the direction of dominant winds. Control areas were selected that were similar to exposure areas on a number of sociodemographic variables so as to limit the potential for confounding. The cancer study used the same exposure zones and control areas and increases were found in incidences of cancers of the stomach, liver, prostate, and lung for men, and stomach and cervix/uterus for women. Incidences of cancers of other organ sites were not increased in the exposed areas. Age and sex were the only confounders that could be controlled for directly and the authors admit that area matching for sociodemographic factors was based on fairly broad zones. The landfill started operation in 1968 and cancer incidence was studied between 1981 and 1988, which allowed a maximum latency of only 20 years among those residents in the area throughout the period.

In Mellery, Belgium, gases containing a complex mixture of VOCs escaped when the clay seal of a landfill site cracked. Because some of the detected chemicals were known mutagens and/or carcinogens, damage to chromosomes was studied and an increase in chromosome damage (sister chromatid exchanges) was found among Mellery residents but not in unexposed subjects in subgroups of both smokers and nonsmokers (15). In children 8–15 years of age, a more marked difference was found between exposed and unexposed groups than among adults. The findings indicated exposures similar to those of occupationally exposed populations. The adult unexposed comparison subjects were recruited from a volunteer blood donor list and may therefore have comprised a group with risk behavior and exposure to possible risk factors for chromosome damage different from those of the general population. They also reported less occupational exposure than the Mellery inhabitants. It is unclear how occupational exposure was defined and results have not been adjusted for it. A follow-up study after site remediation reduced the concentration of the atmospheric pollutants to background levels reported that chromosomal damages in Mellery children had returned to background levels and were no longer different from those for unexposed populations (28).

At the Drake Superfund Site, an industrial chemical dump in Pennsylvania, widespread on- and off-site contamination of groundwater, soil, and surface water with organic (benzene, chlorinated benzene, phthalates) and inorganic (arsenic, mercury) compounds prompted a

cancer mortality and birth defects study (29) and a community health survey (16). Air monitoring near the site identified a small number of organic compounds, but the main exposure route was thought to be direct contact with surface waters and soil in recreational areas near the site. Budnick et al. (29) found an increase in mortality from bladder cancer (cancer of primary a priori concern because of aromatic amines detected on and off site) in the male population of one of the counties surrounding the waste site compared to average mortality rates in the entire state and the United States. Bladder cancer in females did not show such an effect. The authors point out that an occupational effect for males working in the Drake chemical plant may explain the fact that the association was found in men only. No excess in risk of birth defects was found. The subsequent health survey (16) found increased reporting of sleepiness and skin problems in the exposed community and concluded that it was difficult to say whether toxic chemicals from the site, overreporting of symptoms by the exposed community (reporting bias), or other factors such as stress and occupational exposure caused these symptoms.

#### ***Studies of self-reported health symptoms.***

A number of other community health surveys have investigated a wide range of health problems, including respiratory symptoms; irritation of skin, nose, and eyes; gastrointestinal problems; fatigue; headaches; psychological disorders; and allergies. These studies have been conducted in response to concerns from the public, often triggered by smells and odors from the sites. In a number of studies, self-reported health problems were increased in exposed populations (people living close to the waste sites) compared to control populations [Drake Superfund Site (16); Lowell, Massachusetts (17); Hamilton, Ontario (30); Stringfellow, California (31); Queensland, Australia (32); McColl waste site, California (18); Houston, Texas (33); Harris County, Texas (34)] (see Table 1 for details). The majority of these health surveys rely on residents reporting symptoms and diseases through questionnaires or interviews. The possibility exists that higher reporting rates of symptoms in exposed areas are at least partly explained by reporting and/or recall biases. From a public health point of view, the findings of high symptom reporting, whether or not due to differential self-reporting, may indicate the impact that stress and concerns related to landfill can have on ill health and/or perceived ill health. In the survey by Ozonoff et al. (17), residents who indicated they were worried about neighborhood pollution reported more symptoms than those who were not worried, both in the exposed and the control area. Although this does not eliminate the possibility of an effect of toxic chemicals from

the site, it suggests that stress and/or recall bias may have been responsible for the findings. Miller and McGeehin (34) and Dunne et al. (32) found increased symptom prevalence only in residents who indicated they were worried about, or aware of, an environmental problem in their neighborhood. The study by Lipscomb et al. (18) showed a 2-fold risk in most symptoms for residents who were worried compared to those who were not worried among the exposed population. The authors concluded that being worried, rather than a toxicologic effect from the site, explained the symptoms. Hertzman et al. (30) used medical records to confirm certain symptoms and found no over- or underreporting. They concluded that this finding indicated limited reporting bias; however, only a small proportion of the respondents' records were reviewed. Moreover, seeing a physician (and therefore having a medical record) may itself be related to concerns about the site. Baker et al. (31) studied self-reported health problems as well as mortality, cancer incidence, and pregnancy outcomes from medical registers at the Stringfellow waste dump in California. Self-reported diseases and symptoms were the only outcomes that differed between exposed and unexposed areas. Again, a higher perception of threat was related to a higher risk of nearly all self-reported symptoms.

The complicated relation between worry, odor perception, and symptom reporting related to hazardous waste landfill sites is further discussed by several authors (35–37).

Two recent studies around the French landfill of Montchanin used records of prescribed medication (19) and cases from general practitioners (GPs) (20) to define health outcome, in order to avoid biases related to self-reporting of symptoms. Exposure classification in both studies was based on an individual index, taking into account the concentration of airborne pollutants and daily activities of study subjects. High concentrations of VOCs were detected in areas near the site and both leachates and air from the site were reported to be highly toxic in 1988 and 1989, shortly after site closure. Consumption of drugs prescribed for most conditions from 1987 to 1989 did not show a trend with exposure level, although a slight trend was found for drugs taken for ear, nose, and throat, and pulmonary conditions. In the second study, patients with conditions thought to be associated with dump emissions were compared to other GP patients and an association was found for respiratory symptoms and psychological disorders. Again, consulting a doctor for such conditions and subsequent diagnosis of the conditions by the physician may be related to fears of adverse effects from the landfill rather than to toxic chemical effects.

**Cluster Investigations.** In addition to the above papers, a number of reports are available of geographical comparison studies initiated after high rates (clusters) of specific diseases were reported in the vicinity of landfill sites. For example, increased rates of leukemia found in communities nearest a toxic waste dump in North-Rhine Westfalia, Germany, supported a GP report of a cluster near the site (38). A cluster of childhood cancer reported by residents near a landfill site in Walsall, England, was not confirmed in a geographical comparison of rates in the ward containing the site to expected rates based on the regional average (39). Only short reports of these two investigations have been published. Concerns from residents and a GP about increased rates of congenital abnormalities (specifically gastroschisis, a defect in the abdominal body wall) among the population living near the Welsh landfill of Nant-y-Gwyddon were supported by the finding that rates of congenital abnormalities in exposed wards were almost 1.9-fold those in unexposed wards over the period from 1990 to 1996 (40). However, rates in the exposed wards were already high (1.9-fold those of unexposed wards) between 1983 and 1987 before the site opened, and it is unlikely, therefore, that these increased rates were due to the landfill. Four cases of confirmed gastroschisis indicated a significant 9-fold excess in rates of gastroschisis among exposed wards between 1989 and 1996. A cluster of bladder cancer cases in one town in Illinois in the United States, was observed by researchers and subsequently linked to the presence of two contaminated wells close to a landfill site (41).

A general problem in the interpretation of all cluster investigations is that localized areas of high disease density may occur even as part of a random pattern of disease. It is difficult to distinguish clusters derived from this random pattern from those where there is a common underlying local cause (42,43). Also, areas with higher disease densities, although part of the random pattern of disease, may be selectively picked for study.

**Studies of drinking water contamination incidents.** The presence of chemicals in groundwater and drinking water is an important factor in determining the risk posed by landfill sites. However, it does not tell us what effect, if any, the consumption of contaminated water has on human health. Studies of adverse health effects prompted by the contamination of well water used for drinking water and other domestic uses by hazardous substances from waste disposal sites (mainly sites where chemical waste drums were buried) are discussed below. Literature on contaminated water and potential health effects is more extensive than that presented

in this section, which focuses only on water contamination directly related to the disposal of waste. The 1991 review by the National Research Council (2) gives a more comprehensive review of studies on contamination of domestic water supplies and health effects and concludes that although the available literature is scanty and not conclusive, drinking water contamination could lead to adverse health effects. Most of the studies summarized below have been discussed extensively in previous reviews (1,2).

In Woburn, Massachusetts, toxic chemicals (industrial solvents, mainly trichloroethylene) from a waste disposal site were detected in municipal drinking water wells. Residents of Woburn reported a cluster of 12 leukemia cases in children, and a first study confirmed that this number was significantly higher than expected on the basis of national rates (44). The problems with cluster analyses are discussed above. Because of lack of information on exposure to the contaminated wells, it was not possible in this first report to link the leukemia cases with exposure to the well water. Lagakos et al. (45) followed up these findings by compiling an exposure score for residential zones in Woburn using information on what fraction of the water supply in each zone had come from the contaminated wells annually since the start of the wells. Childhood leukemia incidence, perinatal deaths, congenital anomalies, and childhood disorders were studied in relation to the exposure scores. A significant excess was found again comparing leukemia rates for Woburn with national rates, and an association was found between leukemia incidence and exposure scores. The pregnancy outcome survey found associations with eye/ear congenital anomalies and central nervous system/oral cleft/chromosomal anomalies (mostly Down syndrome) but not with low birth weight or most childhood disorders. Pregnancy outcomes were self-reported in this study, but because residents were not aware of their exact exposure scores, the authors conclude that it is unlikely that this led to substantial differential overreporting. Byers et al. (46) undertook a study of 28 family members of patients with leukemia in Woburn. Damage to the immune and nervous systems was found in exposed relatives but not in unexposed controls. Exposure in this study was not measured by exposure to contaminated well water but by being related to a leukemia patient in Woburn, which makes it difficult to interpret the findings. The authors point out that it is impossible to say whether the association is due to an inherited predisposition or to a common environmental exposure of family members to agents that damage the immune system.

A number of studies followed the contamination of two drinking-water wells in Santa Clara County, California, with chlorinated solvents that had leaked from an underground waste storage tank. Residents living near one of the contaminated wells reported a cluster of adverse pregnancy outcomes, mainly spontaneous abortions and congenital heart defects. A first investigation (47) confirmed a significant excess of cardiac anomalies in the service area of the water company that operated the contaminated well compared to those among residents of an unexposed area. The excess was found within the potentially exposed time period and not in an unexposed time period after the well was closed. The authors conclude that the solvent leak was an unlikely explanation for the excess of cardiac anomalies found because the excess occurred mainly in the first 12 months of the exposed time period, and there was a significant ( $p = 0.03$ ) deficit of cases during the second 8 months corresponding to the time when exposure was thought to be more certain. However, it is unclear when the leak started and the potentially exposed period was defined beforehand as the full 20-month period. A second study in the same area reported an increased risk of all congenital malformations combined and spontaneous abortions (48). A follow-up study including a second exposed area did not observe an increase in either outcome in this second area, even though it was thought to have the same water exposure as the original area (49). An exposure study estimating monthly concentrations of solvents in each census tract found no difference in probability of exposure between women with adverse pregnancy outcomes and women with normal births (50). Subsequent studies investigating water consumption in Santa Clara County report significant associations between reported tap water consumption and risk of cardiac defects (51) and spontaneous abortions (52,53), regardless of whether women lived in areas that received contaminated water. As the authors of these studies point out, recall biases cannot be excluded.

In Hardeman County, Tennessee, well water used as drinking water by residents was found to be contaminated with high concentrations of carbon tetrachloride and other chlorinated compounds after complaints were received about the taste of the water. A nearby landfill where 300,000 barrels of pesticide waste had been buried was responsible for the contamination. Analysis of indoor air and bathroom air while showers were running both indicated detectable levels of carbon tetrachloride and other organic compounds in houses that received water from the contaminated wells. Carbon tetrachloride has been identified in toxicologic studies as a strong

liver toxin. The investigation, conducted several months after the population had stopped using the water for drinking, showed abnormally high levels of liver enzymes (indicating liver damage) in residents who had used contaminated water compared to controls, who had not (13). The authors concluded that these high liver enzyme levels probably resulted mainly from exposure due to washing and toilet water uses, and possibly from previous exposure through drinking and cooking. Two months later, when use of the well had completely stopped, liver function in the exposed population had returned to normal. This study benefited from relatively well-documented exposure information and a clear hypothesis about the possible health effects (i.e., liver disease) related to exposure to carbon tetrachloride.

Leakage from an industrial dump of chemical waste drums in New Jersey caused contamination of groundwater and well water with organic chemicals (including benzene, toluene, trichloroethylene, and lead). Najem et al. (54) found higher self-reported prevalence of respiratory disease and seizures but not cancer, liver illness, and skin disease in people living in a high-exposure area estimated on the basis of groundwater flow patterns. Residents in the high-exposure area used private drinking-water wells, ate home-grown food, and smoked more often than populations living in unexposed areas, and when these factors were adjusted for, differences in health outcomes disappeared. Adjusting for possible exposure routes such as local food consumption and use of private wells may have led to overadjustment, however, which would explain why no differences in health outcome were found.

An ex-military base in Dauphin County, Pennsylvania contained drums of toxic chemicals, fly ash, and other waste; well water for homes located on the perimeter of the site was contaminated with trichloroethylene, PCBs, pesticides, and other chemicals (55). Residents were instructed to stop using the water. Higher rates of eye irritation, diarrhea, and sleepiness were reported by residents of households with contaminated well water than by residents of households not having contaminated water.

### Multisite Studies

The problems with single-site studies prompted by community pressures have increasingly been recognized, and recently several large studies have investigated adverse health effects near sets of hundreds of sites selected independently of community concerns or reported disease clusters (Table 2). These studies have the additional advantage of large numbers of subjects, which would give them enough statistical power to detect

small increases in risk of rare diseases such as birth defects and specific cancers. On the other hand, their large scale makes exposure assessment even more complicated than in single-site studies, as adequate information must be collected for each of many sites. A number of the studies discussed below have used the U.S. National Priority Listing (NPL) of hazardous waste sites developed by the U.S. Environmental Protection Agency (U.S. EPA) to select their sites. The NPL ranks all hazardous waste sites in the United States deemed to be of considerable threat to the environment or public health. NPL sites have been relatively well assessed with respect to the potential or actual migration of hazardous chemical substances from the sites through groundwater, surface water, and air (2). Most multisite studies, however, were not able to distinguish between different types and pathways of contamination and, in absence of better exposure data, based their assessments of exposure on distance of residence from the sites or residence in an area with a site. Exposure misclassification, if nondifferential, may be expected to dilute true effects in these investigations. Multisite studies mainly investigated cancers and reproductive outcomes.

**Cancer studies.** Griffith et al. (56) identified 593 NPL sites over the entire United States where contamination of groundwater used for drinking water had been detected by laboratory analyses. Cancer mortality rates for counties containing one or more of these NPL sites were compared to those for counties not containing sites and raised levels of lung, bladder, stomach, and rectum cancer were found. These results were not adjusted for confounding factors such as socioeconomic status and smoking and are therefore difficult to interpret.

A case-control study in New York State (57) examined lung-cancer in relation to residence in a census tract with a waste site. Twelve waste sites known to contain suspected lung carcinogens were studied. A questionnaire survey among next of kin of the deceased cases and controls attempted to collect information on factors such as smoking, diet, education, and residential history. Smoking was significantly more frequent among cases, but there was no association between having lived in or duration of living in an exposed census tract and risk of lung cancer. Low response rates (around 60%) and possible recall bias limit this study.

A recent study in New York State (58) investigated cancer risks near 38 landfills where migration of landfill gas through soil was likely. Migration of soil gas could result in indoor exposure in nearby houses to hazardous VOCs carried with the landfill gas. Potential exposure areas were defined around each site, and extended 250 ft from the

landfill at 36 sites and 500 ft at 2 sites. Incident cases of cancer collected from the New York State Cancer Registry were compared with a random selection of deaths from causes other than cancer, matched by age and sex. Only cancers of the liver, lung, bladder, kidney, and brain, and non-Hodgkin lymphoma and leukemia were studied, as they were regarded potentially sensitive to chemical exposures. Statistically significant excesses in the defined exposure areas were reported only for bladder cancer in women and leukemia in women. The results were adjusted for sociodemographic characteristics of the areas of residence. No information was available on individual factors such as smoking or on how long cases and controls had been living at certain addresses. The use of deceased controls makes interpretation of this study extremely complicated. The deceased population from which controls were selected may differ from the population from which the cases were drawn on a number of variables, including their residence locations.

**Studies of reproductive outcomes.** Shaw et al. (59) conducted a study on the risk of congenital malformations and low birth weight in areas with landfills, chemical dump sites, industrial sites, and hazardous treatment and storage facilities in the San Francisco Bay, California area. Census tracts were classified as *a*) no hazardous site in area, *b*) hazardous site in area but no evidence of human exposure, and *c*) hazardous site and plume in the area with evidence of potential human exposure. A small increase (1.5-fold) in risk was found for heart and circulatory malformations in the areas with potential human exposure. This increased risk was present across chemical classes and exposure routes. Risk of other malformations or low birth weight was not significantly increased. Results were adjusted for some potential risk factors (maternal age, race, sex of child, birth order) but not for socioeconomic status.

Reproductive outcomes have been studied in a number of other multisite studies. Sosniak et al. (60) investigated the risk of adverse pregnancy outcomes for people living within 1 mile of a total of 1,281 NPL sites over the entire United States. The risk for low birth weight and other pregnancy outcomes (infant and fetal death, prematurity, and congenital anomaly) was not associated with living near a site after taking into account a large number of potential confounding factors, including socioeconomic variables collected through questionnaires. However, only around 63% of women originally sampled for the study returned the questionnaire and were included in the study. Also, it is unclear how congenital anomalies were defined, and no subgroups of malformations were studied.

Geschwind et al. (61) investigated the risk of congenital malformations in the vicinity of 590 hazardous waste sites in New York State. A 12% increase in congenital malformations was found for people living within 1 mile of a site. For malformations of the nervous system, musculoskeletal system, and integument (skin, hair, and nails), higher risks were found. Some associations between specific malformation types and types of waste were evaluated and found to be significant. A dose-response relationship (higher risks with higher exposure) was reported between estimated hazard potential of the site and risk of malformation, adding support to a possible causal relationship. However, a follow-up study of Geschwind's findings (62) found no relation between two selected types of malformations (central nervous system and musculoskeletal) and living near a hazardous waste disposal site. The study did report an increased risk of central nervous system defects for those living near solvent- or metal-emitting industrial facilities. Subjects for the first 2 years of this study were also included in Geschwind's study, and 2 more years were studied. Marshall et al. (62) attempted to improve the exposure measurement in the first study by assessing the probability of specific contaminant-pathway combinations in 25 sectors of the 1-mile exposure zones (63). The risk of particular pathways or contaminant groups could not be investigated, however, because of limited numbers of cases in each subgroup. Hall et al. (64) used the same method of exposure assessment to study renal disease near 317 waste sites in 20 counties in New York State. Increased risks were found for associations between renal disease and residential proximity to a site (within 1 mile), the number of years lived near a site, and a medium or high probability of exposure, although the associations did not reach statistical significance.

A study by Croen et al. (65) based exposure measurement on both residence in a census tract containing a waste site and distance of residence from a site. Three specific types of birth defects (neural tube defects [NTDs], heart defects, and oral clefts) were studied; little or no increase in the risk was found using either measure of exposure. Risks of neural tube (2-fold) and heart defects (4-fold) were increased for maternal residence within 1/4 mile of a site, although numbers of cases and controls were too small (between 2 and 8) for these risk estimates to reach statistical significance. Births were ascertained from nonmilitary-base hospitals only, and the authors point out that the increased risk of NTDs may have resulted from lower ascertainment of exposed controls than exposed cases where exposure zones included military bases. Military base residents with pregnancies

affected by NTDs may have been more likely to deliver in nonmilitary hospitals than residents with unaffected pregnancies.

A first European multisite study recently reported a 33% increase in all nonchromosomal birth defects combined for residents living within 3 km of 21 hazardous waste sites in 10 European regions (66). Neural tube defects and specific heart defects showed statistically significant increases in risk. Confounding factors such as maternal age and socioeconomic status did not readily explain the results. The study included both open and closed sites that ranged from uncontrolled dumps to relatively modern controlled operations. This disparity makes it difficult at this stage to conclude, if indeed the association is causal, whether risks are related to landfill sites in general or whether specific types of sites may be posing the risks.

## Conclusions

The presence of large quantities of mixtures of potentially hazardous chemicals in landfill sites close to residential populations has increasingly caused concern. Concerns have led to a substantial number of studies on the health effects associated with landfill sites. From this review we can conclude that increases in risk of adverse health effects have been reported near individual landfill sites and in some multisite studies. Although biases and confounding factors cannot be excluded as explanations for these findings, the findings may indicate real risks associated with residence near certain landfill sites.

For several reasons, evidence is limited for a causal role of landfill exposures in the health outcomes examined despite the large number of studies. Effects of low-level environmental exposure in the general population are by their nature difficult to establish. Also, existing epidemiologic studies are affected by a range of methodologic problems, potential biases, and confounding factors, making the interpretation of both positive (statistically significant increase in risk) and negative (no increase in risk) findings difficult (67). Lack of direct exposure measurement and resulting misclassification of exposure affects most studies and can limit their powers to detect health risks.

It is possible that studies not showing associations have been less likely to be included in this review because they may have been less likely to be submitted or selected for publication, thereby causing the review to be biased toward studies that did report positive associations. However, a number of so-called negative studies have been published and included in this review. We feel that most large, good-quality, epidemiologic investigations, particularly those starting with an *a priori* hypothesis rather than a specific cluster,

would have resulted in publication, whether or not the findings were positive.

An increase in self-reported health outcomes and symptoms such as headaches, sleepiness, respiratory symptoms, psychological conditions, and gastrointestinal problems has been found consistently in health surveys around sites where local concerns were evident (9,16–18,30–34,54,55). In these health surveys symptoms were usually reported by the exposed population without further confirmation of the diagnoses by medical examination. It is not possible at this stage to conclude whether the symptoms are an effect of direct toxicologic action of chemicals present in waste sites, an effect of stress and fears related to the waste site, or an effect of reporting bias (the tendency of exposed people to remember and report more symptoms than unexposed people). Several authors have discussed the possibility that odor complaints and related worry about a site may trigger symptoms of stress-related disease or lead to an increased awareness of existing symptoms (36,37). Further research in this area is urgently needed to improve our understanding of the impact of social factors and risk perceptions on both actual and perceived ill health in waste site communities. Issues of environmental equity and environmental justice must form an integral part of such research.

Evidence for a causal relationship between landfill exposures and cancers is still weak. Cancers are difficult to study because of long latency periods, as discussed in previous sections. Also, cancer studies have mainly compared incidence or mortality rates between geographic areas without collecting adequate information on confounding factors. Excesses in bladder, lung, and stomach cancer and leukemia were reported in more than one study (21,29,41,45,56,58). Well-designed studies with long follow-up and good quality information about confounding factors such as smoking are needed to confirm these findings.

A number of studies have suggested a relationship between residential proximity to landfill sites and adverse pregnancy outcomes. An increase in infants with low birth weights has been the most consistent finding in single-site studies (11,12,14,26,27). These were generally well-designed studies and low birth weight is thought to be a sensitive marker of effects of chemical exposures. Small increases in the risk of birth defects and certain specific birth defects (cardiac defects, central nervous system defects, musculoskeletal defects) have been reported, mainly in multisite studies (12,59,61,65,66). Studies are still too few, however, to draw conclusions regarding causality. Fetuses, infants, and children are generally thought to be more vulnerable and therefore experience toxic effects at lower

doses than the adult population (25). The finding of shorter stature in Love Canal children (10) may also be an example of this.

An increased presence of chromosomal changes was reported in the vicinity of a landfill site in Mellery, Belgium (15,28), but not in Love Canal (8). Findings in Mellery were related to children in particular, which may again be an indication that children are more susceptible to low-level exposures from waste sites. It is not clear at present how well chromosomal changes predict cancer risk in humans.

Other adverse health outcomes such as abnormalities in liver function (13) and in renal disease (64) have also been reported in relation to hazardous waste exposure, although in single studies only.

For the future planning and regulation of landfill sites it is important to know which types of sites are most likely to entail risks. Landfill sites may differ enormously in the conditions that render them hazardous, and conditions that determine the exposure to and resulting health risks posed by any waste site are likely to be unique to that particular site. Such conditions may include the types, quantities, and age of the waste present; hydrogeologic and meteorologic factors; and site management and engineering practices. We have not in this review attempted to relate technical aspects of waste disposal to health effects. Much of the existing epidemiologic work investigates large, old sites, uncontrolled dumps, and sites where heavy off-site migration of chemicals was detected. On the basis of current evidence, we cannot extrapolate findings for these individual sites to landfill sites in general or conclude which landfill sites are more likely than others to affect the health of nearby human populations.

It is also not possible to determine whether sites with airborne or waterborne exposures are more likely to pose a risk to human health. Although drinking water contamination is usually the primary concern related to landfill sites, in most cases local water supplies do not originate from the local area. Most studies, therefore, concern landfill sites where no local drinking-water wells were present and potential exposure was either airborne or through other routes such as direct contact and consumption of home-grown vegetables.

At present information regarding adverse health effects of exposure to landfill sites in European countries is largely lacking.

## Further Research Needs

Research into the health effects of landfill sites is relatively immature, and further research could improve our current understanding (1,2,25,68). Future studies of landfill sites would greatly benefit from a more

interdisciplinary approach, drawing from the fields of landfill engineering, environmental sciences, toxicology, and epidemiology.

Improvements in the base of toxicologic and epidemiologic data on effects of specific chemical exposures would improve our understanding of possible risks of the migration of these chemicals from landfill sites into the environment. Johnson and DeRosa (69), in a recent review of toxicologic hazards of Superfund waste sites, conclude that although a large body of toxicologic research is under way to assess the toxicity of chemicals commonly contaminating the environment surrounding waste sites, equally significant work is still to be done before these chemicals have adequate toxicity profiles that can be used by health and risk assessors. Johnson and DeRosa discuss data needs established by the Agency for Toxic Substances and Disease Registry and the U.S. EPA for research of individual chemicals and find these needs mainly in dose-response studies, reproductive studies, and immunotoxicology studies. Improved data on effects of individual chemical exposures would improve the quality of quantitative risk assessments that can be made for landfill exposures. However, quantitative risk assessments are based to a large extent on unverifiable assumptions, and therefore cannot negate the necessity for direct epidemiologic studies of people living near landfill sites.

More research into effects of chemical mixtures and possible interactions between single chemicals is needed to improve understanding of effects of multiple chemical exposures. Such research is complex, but new research initiatives are under way, mainly in the United States. For example, the U.S. EPA MIXTOX database, which contains toxicologic data on interactions of hundreds of pairs of chemicals, is a promising new development (70). Research developments and future directions in this field are discussed in detail by a number of authors (70–72).

The investigation of single landfill sites is important as a response to community concerns. More multisite studies with large study populations should also be conducted to draw conclusions about more general risks. Ideally, such multisite studies should attempt to classify sites in such a way that risks related to specific site characteristics can be investigated. However, systematic site assessments needed to underpin such classifications are at present totally lacking in Europe. There is little detailed information on waste inputs, especially for old landfills, and monitoring practices vary hugely for factors such as frequency of monitoring, the environmental media monitored, and types of chemicals monitored. Standardized waste-input recording systems and monitoring practices across

European countries and the availability of summary reports of waste inputs and monitoring results would aid site classifications for epidemiologic studies as well as risk assessments. A recent report evaluating the use of a risk assessment tool on two U.S. and three U.K. landfill sites concluded that in the United Kingdom it is not possible to characterize the majority of landfills, even to the level at which a simple risk assessment framework can be employed on a site-specific basis. This particularly applies to the characterization of emplaced waste (73).

Epidemiology has increasingly made use of so-called biomarkers—biological monitors of either the internal dose of a chemical (biomarkers of exposure) or the biologic response to exposure (biomarkers of early effect). Biomarkers of the first type measure levels of chemicals in human tissue and fluids (e.g., blood, urine). These techniques can generally measure only a small number of chemicals, and their use is limited to situations in which environmental monitoring data indicate specific landfill chemicals that are of particular concern. The presence of chemicals in the body is currently difficult and costly to measure, but this may change. Biomarkers of the second type measure biological responses such as chromosomal changes (sister chromatid exchanges) and molecular changes (DNA adducts), and could be seen as early effect manifestations. Interpretation of these effect biomarkers is difficult; their link with clinically overt disease remains unclear, but their use could give studies much greater statistical power than studies of rare disease outcomes. Biomarker techniques have been used mainly in occupational settings and there has been less discussion of their use in environmental studies (74,75). Collaboration is required between epidemiologists and basic scientists to further develop biomarker techniques for use in studies of environmental exposures.

Specific areas of further research likely to prove most useful are

- The study of vulnerable groups—groups of the population likely to develop adverse health effects at levels of exposure lower than those of the general population. Such groups include: fetuses, infants, and children; elderly people; and people with impaired health.
- The study of people with higher exposures, for example, children (because they come into higher contact with potentially contaminated soil); people who eat local food products; workers at waste sites; people with life-styles (possibly socio-economically determined) that lead to higher exposures.
- The study of worst-case landfills. In the absence of adequate exposure data, it is difficult to define worst-case sites.

Ranking systems are in use, e.g., in the Superfund program (76), to rank waste sites according to their hazard potential, but their application generally requires extensive site investigations. Few epidemiologic studies would have the resources to carry out such investigations. It could be argued that identification of worst-case landfills should form part of regulatory practice in Europe. However, in the absence of systematic investigation of this kind, the study of sites where high off-site contamination has been detected and sites that have been subject to less regulation (possibly sites in developing countries or Eastern Europe) could be suitable for the study of worst-case scenarios provided appropriate health data can be collected.

It is possible with suitable investment to improve levels of understanding about risks of hazardous wastes to human health. However, because of the complicated nature of the exposure, it is likely that there will always remain a degree of uncertainty regarding health effects of landfill sites.

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# Mortality among Former Love Canal Residents

Lenore J. Gensburg,<sup>1</sup> Cristian Pantea,<sup>2</sup> Edward Fitzgerald,<sup>1</sup> Alice Stark,<sup>2</sup> Syni-An Hwang,<sup>2</sup> and Nancy Kim<sup>2</sup>

<sup>1</sup>University at Albany, State University of New York, Albany, New York, USA; <sup>2</sup>New York State Department of Health, Troy, New York, USA

**BACKGROUND:** The Love Canal is a rectangular 16-acre, 10-ft deep chemical waste landfill situated in a residential neighborhood in Niagara Falls, New York. This seriously contaminated site first came to public attention in 1978. No studies have examined mortality in the former residents of the Love Canal neighborhood (LC).

**OBJECTIVE:** The aim of this study was to describe the mortality experience of the former LC residents from the years 1979–1996.

**METHODS:** From 1978 to 1982, 6,181 former LC residents were interviewed. In 1996, 725 deaths from 1979–1996 were identified in this cohort, using state and national registries. We compared mortality rates with those of New York State (NYS) and Niagara County. Survival analysis examined risks by potential exposure to the landfill.

**RESULTS:** We were unable to demonstrate differences in all-cause mortality for either comparison population for 1979–1996. Relative to NYS, the standardized mortality ratio (SMR) was elevated [SMR = 1.39; 95% confidence interval (CI), 1.16–1.66] for death from acute myocardial infarction (AMI), but not relative to Niagara County. Death from external causes of injury was also elevated relative to both NYS and Niagara County, especially among women (SMR = 1.95; 95% CI, 1.25–2.90).

**CONCLUSIONS:** The role of exposure to the landfill in explaining these excess risks is not clear given limitations such as multiple comparisons, a qualitative exposure assessment, an incomplete cohort, and no data on deaths prior to 1978. Lack of elevation for AMI when compared with Niagara County but not NYS suggests possible regional differences. However, direct cardiotoxic or neurotoxic effects from landfill chemicals or indirect effects mediated by psychological stress cannot be ruled out. Revisiting the cohort in the future could reveal patterns that are not yet apparent.

**KEY WORDS:** community health, exposure assessment, hazardous waste sites, Love Canal, mortality. *Environ Health Perspect* 117:209–216 (2009). doi:10.1289/ehp.11350 available via <http://dx.doi.org/> [Online 1 October 2008]

The Love Canal is a rectangular 16-acre, 10-ft deep landfill centered in a residential neighborhood in northwestern New York State (NYS). The trench was originally dug in 1894 by William T. Love to connect the upper and lower Niagara Rivers, thereby providing cheap hydroelectric power. The landfill was one of the most seriously contaminated hazardous waste sites in the United States, containing approximately 21,800 tons of at least 200 different chemicals disposed by Hooker Chemical and Plastics Corporation from 1942 to 1953 [NYS Department of Health (NYSDOH) 1981]. According to company records, these chemicals were predominantly hexachlorocyclohexanes (e.g., lindane); benzylchlorides; organic sulfur compounds (e.g., lauryl mercaptans); chlorobenzenes; and sodium sulfide/sulphydrates.

Contamination of homes adjacent to the landfill became apparent in 1978, with the potentially exposed population including several hundred residents within one block of the landfill and almost 3,000 residents within approximately four blocks (NYSDOH 1981). Environmental sampling, begun in the late 1970s, focused on indoor air, particularly in the basements and living spaces of homes closest to the landfill. Subsequent sampling included soil, sediments, water, leachate, and some biota. Possible migration routes, such as storm sewers and historic swales, were also examined. Excavation of the major swale

found no evidence of migration along its bottom, but scattered, low-level contamination of the fill material suggested that chemically contaminated soils were used to fill the swales (Kim et al. 1982).

By 1980, several state and federal emergency declarations led to an emergency appropriation that helped purchase residences in the larger neighborhood surrounding the landfill, known as the Emergency Declaration Area (EDA) (Figure 1). This man-made disaster also prompted the passage of the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) by the U.S. Congress in 1980 (CERCLA 1980). This legislation authorized federal funding for Superfund remedial activities at hazardous waste sites nationwide.

In response to this situation, a number of health studies of the Love Canal neighborhood (LC) residents were conducted by the NYSDOH, the U.S. Environmental Protection Agency (EPA), and independent researchers. These studies examined blood counts and liver function tests (NYSDOH 1981), blood level of semivolatiles (Bristol et al. 1982), cytogenetic abnormalities and sister chromatid exchange (Heath et al. 1984; Picciano 1980), nerve conduction velocity (Barron 1982), rates of drug metabolism (Cuddy et al. 1984), cancer incidence (Janerich et al. 1981), low birth weight (Goldman et al. 1985; Vianna and Polan

1984), congenital malformations (Goldman et al. 1985; Paigen 1982), children's growth rates (Paigen et al. 1987), and problems in childhood development (Paigen et al. 1985). The results of these studies were largely equivocal or contradictory, and none of the follow-up periods extended beyond 1982.

Concerns about long-term health effects due to residential exposure to the landfill prompted more recent research. In 1996, the NYSDOH began a series of studies to describe the health status of the former residents and their children through 1996. In 1998, an expert advisory committee was convened to provide advice and guidance. A year later, three former LC residents were added to the committee to provide community input. The objective of this study was to describe the findings for overall and cause-specific mortality by *a*) characterizing the mortality experience of the cohort from 1978 through 1996 compared with NYS [exclusive of New York City (NYC)] and Niagara County, and *b*) modeling mortality with regard to measures of potential exposure to chemicals from the landfill.

## Materials and Methods

**Study area and population.** This follow-up health study cohort is based on the cohort that was identified and interviewed by the NYSDOH from 1978 to 1982. The 6,181 former residents included in the present study lived in the LC EDA any time between 1940 and June 1978, and were interviewed in 1978–1982 or, if < 18 years of age, one or both parents were interviewed.

Although Hooker Chemical did not begin using the trench to dump chemical waste until 1942, there was anecdotal evidence that chemical and municipal wastes were deposited there before 1942 (State of New York 1978). Because only 2.6% of the cohort lived in the EDA prior to 1940 and given that there is

Address correspondence to C. Pantea, NYSDOH/CEH, 547 River St., Room 200, Troy, NY 12180 USA. Telephone: (518) 402-7950. Fax: (518) 402-7959. E-mail: cip03@health.state.ny.us

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no clear date when waste was first deposited, 1940 was chosen as the year to begin exposure assessment. The date of entry into the study was the interview date; children were assigned the interview date of their parent.

By consulting City of Niagara Falls directories from the years 1940–1980 and using field staff to physically locate homes in 1978, we determined that there were 814 single-family homes in the EDA. Using information from the interviews, we found that of these homes, 776 (95%) were occupied by at least one member of the cohort sometime between 1940 and 1978, and 575 (74%) of the 776 homes were occupied by one or more members of the cohort for at least 75% of the time. A large portion of the EDA to the west of the landfill contained, sequentially, two public housing projects: Griffin Manor,

which was torn down in the 1960s, and the LaSalle Development. Neither the number of apartments nor who resided in these projects is known; real property information is not available by apartment. The NYSDOH attempted to interview all residents living in the LaSalle project in 1978 by going door-to-door and setting up tables in the lobbies of the buildings, but the success rate of this attempt to include residents of the project is unknown. This interviewing process yielded 1,315 members of the cohort (21.3%) who resided in at least one of these rental units.

**Comparison populations.** We chose New York State as a reference population because it was sufficiently large to provide stable death rates by year, age group, and sex (U.S. Census Bureau, Washington, DC). The five boroughs of NYC were excluded because their greater

ethnic diversity would introduce potential confounding that could not be adjusted for in the analyses. Niagara County provided a comparison population very similar to the LC cohort demographically, while mitigating any potential regional differences in identifying the primary cause of death. Niagara County also allowed an attempt to control for possible local environmental sources of chemicals other than the landfill itself.

**Tracing of the cohort.** We traced the 6,181 members of the cohort beginning in 1996 extending back to the date of their interview (1978–1982) to determine their current vital status and, if deceased, the date of death. The names of all females were first submitted to the NYS Vital Records (NYSVR) to be matched to the marriage registry for possible name changes. All names (e.g., birth, marriage) of both male and female members of the cohort were then matched to the Social Security Death Index database (ancestry.com 2009). The names of those not known to be dead were searched using NYS Department of Motor Vehicles (Albany, NY) files, Internet telephone directories, the U.S. Post Office Address Correction Service (U.S. Postal Service, Washington, DC), and the NYSVR Death Registry (NYSDOH Vital Records Bureau, Albany, NY). As a last resort, we contacted family members or former neighbors.

**Exposure assessment.** In addition to comparisons with NYS and Niagara County, we conducted internal comparisons among members of the cohort using the potential for exposure of each resident to the landfill. We created an exposure matrix after a comprehensive review of files from the historical records (e.g., documented use of the landfill, odor complaints), environmental sampling data, and numerous interpretive reports. The matrix focused on location and time of residence plus three additional exposure-related variables: childhood exposure, attending the 99th Street School, and living in a residence on an environmental “hot spot” or historic swale.

Location was defined by dividing the EDA, respectively, into four areas, or tiers: tiers 1 and 2, respectively, were contiguous to or across the street from the landfill; tiers 3 and 4 were farther away (Figure 1). Two distinct time periods of potential chemical exposure were identified: 1942–1953 and 1954 until evacuation (1978 for tiers 1 and 2 and 1980 for tiers 3 and 4). The few homes in tiers 1 and 2 in the earlier period would have been the most highly affected; all other residences were relatively less affected. Contaminants may have entered yards and homes through air transport and deposition, surface water runoff, and shallow groundwater transport during this period, especially in tier 1 (NYSDOH 1981).

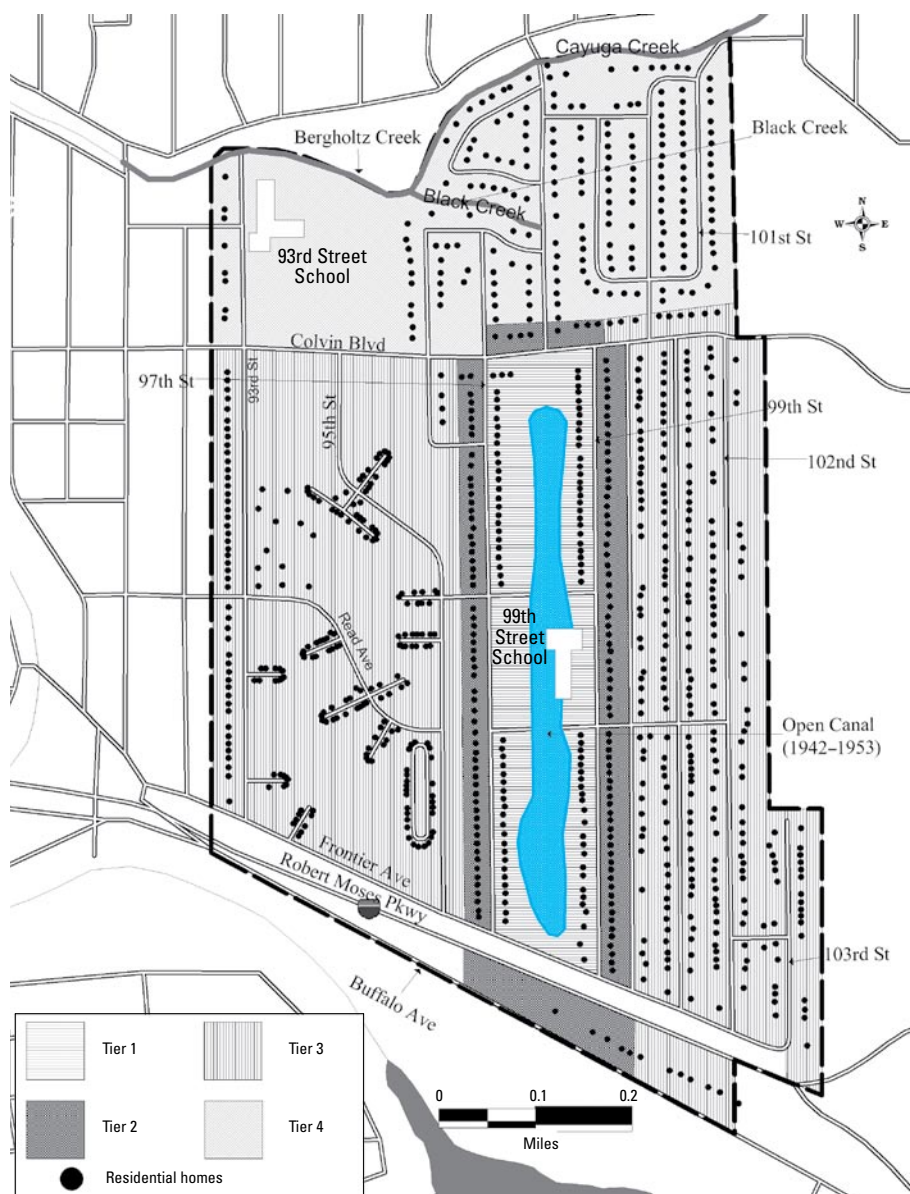


Figure 1. Emergency declaration area.

The closed period began in 1954 when the landfill was covered and construction of homes in the area immediately adjacent was begun. These homes were situated such that either their back yards were contiguous with or directly across the street from the covered landfill. Odor complaints were made to local officials as early as the late 1950s and continued through 1978. The indoor environmental sampling of homes began in 1978, and > 800 air samples from 400 houses were collected. For chlorobenzene and chlorotoluene, the highest levels of contamination were in homes nearest the landfill (NYSDOH 1981). Thus, the historic and environmental evidence suggested a potential for exposure from 1954 until evacuation.

Individual residential history was determined and classified by time period and tier. Because of colinearity problems in the regression, tiers 1 and 2 were combined, as were tiers 3 and 4. The resulting variables consisted of four categories of potential residential exposure: *a*) open period, tiers 1 and 2; *b*) open period, tiers 3 and 4; *c*) closed period, tiers 1 and 2; and *d*) closed period, tiers 3 and 4. Cumulative exposure consisted of the number of years each study participant lived in each of the four tier/time categories. These exposure estimates were not mutually exclusive, as many cohort members fell into more than one of the categories.

Childhood exposure was dichotomously defined as additional potential for exposure among children. Anecdotal evidence suggested that teenaged boys swam in the water-filled trench during the years of active dumping; therefore, 13- to 18-year-old males were considered potentially exposed in childhood from 1942 to 1953. After 1954, children < 13 years of age who lived closest (tiers 1 and 2) played on the soil covering the landfill and were therefore also considered potentially exposed during childhood. A second dichotomous variable indicated whether the cohort member lived in a residence either built on one of the natural historic swales or where the 1978 sampling results indicated higher than expected levels of chemical contaminants in the soil. The third additional exposure variable was the number of years of attendance at the 99th Street School, which had been built directly adjacent to the landfill.

To assess the sensitivity of the results because of the exposure definition used, we modeled three additional exposure classifications. One consisted of the total number of years a study participant resided in the EDA, irrespective of time period, location, or age. The remaining two definitions were based on four variables using age ( $\leq 18$  years and  $> 18$  years) and tier: *a*)  $\leq 18$  years, tiers 1 or 2; *b*)  $\leq 18$  years, tiers 3 or 4; *c*)  $> 18$  years, tiers 1 or 2; and *d*)  $> 18$  years, tiers 3 or 4. One definition quantified cumulative exposure using

the number of years of residence in each of these four age and location combinations; the other dichotomized the four variables as ever/never. Because the latter definition used indicator variables, the analyses were performed on a subset of the cohort in which the resulting variables were mutually exclusive.

**Outcome assessment.** To obtain cause of death, the names of cohort members who were known to have died in the study period were matched with the NYSVR Death Certificate Registry (NYSDCR) and, if they died out of state, with the National Death Index (NDI) of the National Center for Health Statistics (Hyattsville, MD). First and any known last names, sex, race and dates of birth were submitted to the NYSDCR and/or NDI, and the underlying cause of death was abstracted using the *International Classification of Diseases, Ninth Revision* (ICD-9; Department of Health and Human Services 1989).

The Centers for Disease Control and Prevention's (CDC) Wide-Ranging Online Data for Epidemiologic Research (CDC-WONDER; CDC 2007), a county-level national mortality and population database, was the source of the comparison mortality data. The mortality database is derived from records of deaths reported by each state's vital records departments and reports all deaths for ages  $\geq 1$  year. Data were collected by sex and age group for each year from 1979 to 1996. The preassigned age groups used by CDC-WONDER are 1–4, 5–9, 10–14, 15–19, 20–24, 25–34, 35–44, 45–54, 55–64, 65–74, 75–84, and  $\geq 85$  years. Data from each year were then grouped for analysis purposes as follows: June, 1978–1981, 1982–1986, 1987–1991, and 1992–1996. Deaths that occurred in the last 6 months of 1978 were considered to have the same rates as 1979. Data were included for any three-digit category of the ICD-9 for which there was at least one event in the cohort.

**Potential confounders.** To control for potential confounding of the association between mortality and exposure, variables were abstracted from the 1978–1982 interviews. We abstracted information such as sex, date of birth, race, occupational narratives, and a history of cigarette smoking and alcohol consumption. The latter two variables were coded as ever/never. Occupational histories included job titles, company names, and dates of employment. NYSDOH industrial hygienists reviewed this information to evaluate each job's potential for exposure to LC indicator chemicals (LCICs) as high, medium, or low/none. LCICs included chemicals such as  $\beta$ -hexachlorocyclohexane, 2-chloronaphthalene, and 1,2,4-trichlorobenzene, known to have been deposited into the landfill and used to assess habitability of the EDA after containment (NYSDOH 1988).

### Statistical analysis. External comparisons.

We computed person-years for the LC cohort as the difference of the date of interview to the date of death, loss to follow-up, or end of the study period (31 December 1996). We used a midyear assignment for persons for which only the year of death or loss to follow-up was known. Rates for each year group, age group, and sex were calculated for both NYS and Niagara County using the three-digit ICD-9 codes, both individually and grouped by organ system. Annual interpolations of the U.S. Census (U.S. Census Bureau, Washington, DC) were used to provide population estimates. The resulting rates were then multiplied by the respective person-years of observation for the LC cohort to calculate expected numbers of cases. Point estimates for standardized mortality ratios (SMRs) were computed as the ratio of observed to expected cases, and 95% confidence intervals (CIs) based on the Poisson distribution were calculated without adjustment for multiple comparisons. These age-adjusted and time period-adjusted SMRs were also calculated separately by sex for both NYS and Niagara County. Adjustments for race were not necessary because the percentages of whites in LC, NYS, and Niagara County were similar (95%, 93%, and 94%, respectively).

**Internal comparisons.** We used survival analysis, specifically the Cox proportional hazards model (Allison 1995; Hosmer and Lemeshow 1999), to model the association between the potential environmental exposure risk factors and survival time among members of the LC cohort; we also calculated hazard ratios (HRs). In keeping with the exploratory nature of the analysis, the models include all relevant environmental exposures and confounders, regardless of the resulting *p*-values.

The analyses focused on six categories of underlying cause of death: all causes; neoplasms (ICD-9 codes 140–239); circulatory system diseases (ICD-9 codes 390–459); acute myocardial infarction (AMI), a subset of circulatory system diseases (ICD-9 codes 410); respiratory system diseases (ICD-9 codes 460–519); and external causes of injury and poisoning (ICD-9 codes E800–E999). We chose these categories because of the large numbers of deaths experienced by the cohort in these groups.

Details concerning the study methodology have been published previously (NYSDOH 2008).

## Results

The LC cohort consists of 6,181 men, women, and children, of which 5,241 (84.8%) were known to be alive in 1996 with a known address; 725 (11.7%) died sometime in the follow-up period; 13 (0.2%) were known to be alive in 1996 but their current address was unknown; and 47 (0.8%) were lost to follow-up between the date of the interview and 1996.

(Table 1). The demographic characteristics of the cohort by tracing status are presented in Table 2. In general, those traced and not traced were similar except those traced were slightly older (median age of 29 vs. 22 years) and therefore lived in the EDA slightly longer (8.5 vs. 5.0 years). More significantly, those traced were more likely to have lived only in single-family homes (78% vs. 51%, respectively;  $p < 0.0001$ ). For the traced cohort, the median amount of time from first residential exposure to the end of the follow-up was 32 years (data not shown).

**External comparisons.** After excluding 155 persons lacking vital status information, the remaining 6,026 people contributed 97,926 person-years to the analyses. Of the 725 deaths observed during the study period, 701 had cause-specific information; the remaining 24 deaths were reported by relatives and the cause was unknown. The latter deaths were included in all-cause mortality but omitted from cause-specific analyses.

Table 3 displays SMRs for females and males separately and with the sexes combined, with NYS as the standard population. Data are presented for specific causes with  $\geq 10$  expected deaths or a combination of an SMR  $> 1.0$  and expected deaths  $> 5$  for males and females combined. We discuss data using Niagara County as the standard population when they differ from those for NYS. Niagara County data have been reported previously (NYSDOH 2008).

For all-cause mortality, the SMR was 1.04 (95% CI, 0.96–1.12); for females, SMR = 1.00 (95% CI, 0.89–1.12); and for males, SMR = 1.06 (95% CI, 0.96–1.17). Similar to NYS and Niagara County, circulatory system diseases were the most common cause of death among the LC cohort (308 deaths; 42.5% of total). The SMR for men and women combined was 1.01 (95% CI, 0.90–1.13); for women alone, SMR = 0.93 (95% CI, 0.78–1.11); and for men, SMR = 1.06 (95% CI, 0.92–1.23). Death from an AMI was the most common in this category and was consistently elevated for both men (SMR = 1.37; 95% CI, 1.08–1.71) and women (SMR = 1.43; 95% CI, 1.06–1.89). Cerebrovascular disease deaths were elevated in men only ( $n = 20$ ; SMR = 1.13; 95% CI, 0.69–1.75). When using Niagara County as the standard population, the only important difference was the null finding for AMI [SMR in men = 1.00 (95% CI, 0.79–1.24); SMR in women = 1.04 (95% CI, 0.77–1.38)].

The second most common cause of death category among both reference populations and among the LC cohort was neoplasms (189 deaths; 26.1% of total). SMRs for neoplasms were  $\leq 1.00$  for both sexes combined and for men and women separately. For cause-specific analyses, the only SMR  $> 1.00$  among women was 1.11 (95% CI, 0.71–1.65) for digestive system neoplasms, and among men, lymphatic and hematologic neoplasms (SMR = 1.06; 95% CI, 0.53–1.90) and other

and unspecified sites (SMR = 1.52; 95% CI, 0.81–2.60).

Unlike NYS or Niagara County, the third most common cause of death category in the LC cohort was external causes of injury and poisoning (62 deaths; 8.6%). The SMR was 1.41 (95% CI, 1.08–1.81) for both sexes combined. This excess risk was greater among women (SMR = 1.95; 95% CI, 1.25–2.90) compared with men (SMR = 1.20; 95% CI, 0.85–1.65). Women had elevated SMRs for suicides (SMR = 2.35; 95% CI, 0.76–5.48), motor vehicle accidents (SMR = 2.12; 95% CI, 1.02–3.89), and other types of accidents (SMR = 1.52; 95% CI, 0.56–3.31). Suicides (SMR = 1.52; 95% CI, 0.79–2.66) and other types of accidents (SMR = 1.33; 95% CI, 0.69–2.32) were also elevated for men.

**Internal comparisons.** Of the 6,026 traced cohort members, 5,974 had known vital status and dates of residence in the EDA. Of these, 706 were deceased, 5,221 were alive through 1996, and 47 were lost to follow-up some time after their interview and before 31 December 1996. Analyses were performed on the subset of 3,796 adults with complete interview data (85.2% of those interviewed) to control for possible confounders such as smoking, alcohol consumption, and occupation. The full study cohort and subset of interviewees were similar with respect to sex, race, and residence in the open period (data not shown). By definition, the interviewees, who had to be at least 18 years old to participate, were older and had longer residencies in the closed period than the cohort as a whole. For brevity's sake, we present only the models for adults with complete interview data. The results for the models based on the complete cohort were virtually identical with respect to the exposure variables of interest.

As shown in Table 4, the risk for all-cause mortality increased with age (HR = 1.10; 95% CI, 1.09–1.10) and was higher among males (HR = 1.65; 95% CI, 1.36–2.02) and smokers (HR = 1.66; 95% CI, 1.35–2.05). The only elevated HR for all-cause mortality among the exposure variables was for childhood exposure (HR = 1.14; 95% CI, 0.54–2.42), but the number of deaths was small ( $n = 9$ ). Age and male sex were also positive associations with several specific causes of death. For AMI, sex was time dependent, requiring an interactive term to be added to the model. Risk of death from AMI among males was greatest at the beginning of the follow-up period (HR = 4.28; 95% CI, 1.79–10.21) and decreased over the 18 years of follow-up (HR = 0.91). Smoking was also positively associated with cause-specific mortality risk: HRs ranged from 1.34 (95% CI, 0.84–2.12) for deaths from AMI to 6.23 (95% CI, 2.15–18.02) for deaths from respiratory system disease.

The four residential exposure variables representing tier and time period showed

**Table 1.** Results of tracing the 6,181 members of the Love Canal cohort.

| Tracing results                                               | No. (%)      |
|---------------------------------------------------------------|--------------|
| Known to be alive in 1996 and current address is known        | 5,241 (84.8) |
| Known to have died in the follow-up period 1978–1996          | 725 (11.7)   |
| Known to be alive in 1996 but current address is unknown      | 13 (0.2)     |
| Lost to follow-up sometime from the date of interview to 1996 | 47 (0.8)     |
| No information available                                      | 155 (2.5)    |
| Total                                                         | 6,181        |

**Table 2.** Demographic characteristics [no. (%)] of the Love Canal cohort ( $n = 6,181$ ).

| Cohort characteristics    | Traced       | Not traced |
|---------------------------|--------------|------------|
| Total                     | 6,026        | 155        |
| Race                      |              |            |
| White                     | 5,717 (95.2) | 130 (85.0) |
| Black                     | 239 (4.0)    | 19 (12.4)  |
| Other                     | 48 (0.8)     | 4 (2.6)    |
| Sex                       |              |            |
| Male                      | 2,914 (48.4) | 50 (32.7)  |
| Female                    | 3,112 (51.6) | 103 (67.3) |
| Residence type            |              |            |
| Single-family homes only  | 4,699 (78.0) | 79 (51.0)  |
| Public housing only       | 747 (12.4)   | 65 (41.9)  |
| Public and single family  | 580 (9.6)    | 11 (7.1)   |
| Year of entry into study  |              |            |
| 1978                      | 3,069 (50.9) | 97 (62.6)  |
| 1979                      | 652 (10.8)   | 10 (6.4)   |
| 1980                      | 676 (11.2)   | 17 (11.0)  |
| 1981                      | 1,353 (22.5) | 25 (16.1)  |
| 1982                      | 276 (4.6)    | 6 (3.9)    |
| Living in the EDA in 1978 |              |            |
| Yes                       | 3,099 (51.4) | 92 (59.4)  |
| No                        | 2,927 (48.6) | 63 (40.6)  |

little association with cause-specific mortality (Table 4) with the exception of the closed period, tiers 1 or 2 for deaths from AMI (SMR = 1.06; 95% CI, 1.01–1.13). This finding was also time dependent; as the follow-up period progressed, the risk decreased to 0.99. The small numbers of residents living on a hot spot or a historic swale had no deaths from respiratory disorders or external causes of injury. The HR associated with attendance at the 99th Street School was elevated only for external causes of injury (HR = 1.12; 95% CI, 0.94–1.32). Childhood exposure had elevated HRs for both deaths from neoplasms and AMI, but the CIs were very wide because of small numbers, and no deaths from respiratory disease were observed for this variable.

## Discussion

These analyses were exploratory. The results describe the mortality status of the LC cohort and suggest directions for future research. Thus, we analyzed the data in several ways using more than one definition of exposure. No single finding should be overemphasized; interpretable, coherent patterns of findings are more likely to indicate valid and meaningful associations. For example, emphasis should be given to similar results when compared with both external control groups, along with those that showed consistent associations. It is also important to exercise caution in that, given the large number of statistical comparisons made, the likelihood of committing a type 1

error is much greater than the nominal 5%. Finally, qualitatively, the width of the CI is very informative: extremely wide CIs indicate that the findings are imprecise.

In the present study we were unable to demonstrate a difference in all-cause mortality for the years 1979–1996 compared with either NYS (exclusive of NYC) or Niagara County; we also could not detect differences for most individual causes of death. The most notable exceptions were deaths from AMI and from external causes, using the NYS reference population. When Niagara County was used as the comparison, the number of deaths from external causes remained excessive, but the death rate from AMI was no longer elevated. Consequently, it is possible that the excess mortality from AMI among LC residents relative to NYS is due to regional differences in mortality rates or in cause of death coding.

Comparison with earlier LC studies is not possible because no other investigation focused on mortality as an end point. However, in a study of another Niagara Falls waste site, no excess in cancer mortality was detected in three surrounding census tracts from 1973 to 1982 (NYSDOH, unpublished data), a finding consistent with that observed in the present study. Some other hazardous waste site studies have reported elevated mortality from specific cancers (Najem and Greer 1985; Najem et al. 1983, 1985; Najem and Molteni 1983), but others have not (Baker et al. 1988; Budnick et al. 1984; Najem et al. 1984,

1994; Polednak and Janerich 1989). Dunne et al. (1990) reported negative findings in an Australian population. Similarly, in a study of a community in South Wales surrounding a landfill site, Fielder et al. (2000) found no excess in all-cause mortality, cancer mortality, or respiratory disease. This study population lived within 3 km of a site used for household, commercial, and industrial wastes, and, like the LC landfill, the residents complained about noxious odors emanating from the site.

Assuming the observed associations of living in the EDA, with mortality from AMI, motor vehicle accidents, and suicides representing a causal relationship, one may postulate two possible pathways: *a*) direct cardiotoxic or neurotoxic effects leading, through biological mechanisms, to heart disease or to psychologic or behavioral symptoms; and *b*) indirect stress-induced physiologic or psychologic reactions, including elevated blood pressure and/or injurious behavioral reactions.

Neurotoxic effects have been reported from occupational exposure to organic solvents, largely among industrial painters (Parkinson et al. 1990; Triebig et al. 2000). At a community level, there is evidence for neuropsychologic effects, including anxiety and depression, from exposure to trichloroethylene (associations that were strongest in the context of alcohol consumption) (Reif et al. 2003). Among farmers, similar effects were associated with organophosphate pesticides (Beseler and Stallones 2003; Stallones and Beseler 2002).

**Table 3.** SMR, year and age adjusted, for females and males separately and combined compared with NYS (exclusive of NYC).

| Cause of death                          | Females      |                   |                        | Males    |                   |           | Combined |           |
|-----------------------------------------|--------------|-------------------|------------------------|----------|-------------------|-----------|----------|-----------|
|                                         | Observed     | SMR               | 95% CI                 | Observed | SMR               | 95% CI    | SMR      | 95% CI    |
| All causes                              | 309          | 1.00              | 0.89–1.12              | 416      | 1.06              | 0.96–1.17 | 1.04     | 0.96–1.12 |
| Infectious disease                      | <sup>a</sup> | 0.43              | 0.05–1.54              | 11       | 1.27              | 0.63–2.26 | 0.97     | 0.52–1.66 |
| Human immunodeficiency virus            | 0            | —                 | —                      | 7        | 1.36              | 0.55–2.81 | 1.04     | 0.45–2.31 |
| Neoplasm                                | 83           | 0.87              | 0.69–1.08              | 106      | 1.00              | 0.82–1.21 | 0.94     | 0.81–1.08 |
| Digestive system                        | 24           | 1.11              | 0.71–1.65              | 25       | 0.89              | 0.57–1.31 | 0.98     | 0.73–1.30 |
| Respiratory system                      | 21           | 0.99              | 0.61–1.52              | 36       | 0.97              | 0.68–1.34 | 0.98     | 0.74–1.27 |
| Bone, connective tissue, skin           | 12           | 0.54 <sup>b</sup> | 0.28–0.95              | —        | —                 | —         | 0.71     | 0.42–1.12 |
| Genitourinary tract                     | 12           | 0.91              | 0.47–1.59              | 14       | 0.91              | 0.50–1.52 | 0.91     | 0.59–1.33 |
| Other and unspecified site              | 5            | 0.67              | 0.22–1.55              | 13       | 1.52              | 0.81–2.60 | 1.12     | 0.66–1.77 |
| Lymphatic and hematologic               | 8            | 0.99              | 0.43–1.95              | 11       | 1.06              | 0.53–1.90 | 1.03     | 0.62–1.61 |
| Endocrine and metabolic disease         | 7            | 0.81              | 0.33–1.67              | 7        | 0.82              | 0.33–1.69 | 0.82     | 0.45–1.37 |
| Other endocrine glands                  | 7            | 0.99              | 0.40–2.04              | 6        | 0.90              | 0.33–1.97 | 0.95     | 0.50–1.62 |
| Diseases of the circulatory system      | 125          | 0.93              | 0.78–1.11              | 183      | 1.06              | 0.92–1.23 | 1.01     | 0.90–1.13 |
| AMI                                     | 49           | 1.43 <sup>b</sup> | 1.06–1.89              | 77       | 1.37 <sup>b</sup> | 1.08–1.71 | 1.39     | 1.16–1.66 |
| Chronic ischemic heart disease          | 30           | 0.70              | 0.47–1.00 <sup>+</sup> | 51       | 0.90              | 0.67–1.18 | 0.81     | 0.65–1.01 |
| Other form of heart disease             | 20           | 0.91              | 0.55–1.40              | 22       | 0.85              | 0.53–1.28 | 0.87     | 0.63–1.18 |
| Cerebrovascular diseases                | 16           | 0.73              | 0.42–1.19              | 20       | 1.13              | 0.69–1.75 | 0.91     | 0.64–1.26 |
| Diseases of the respiratory system      | 29           | 1.20              | 0.81–1.73              | 28       | 0.93              | 0.62–1.34 | 1.05     | 0.79–1.36 |
| Pneumonia and influenza                 | 8            | 0.89              | 0.38–1.75              | 7        | 0.69              | 0.28–1.42 | 0.78     | 0.44–1.29 |
| Chronic obstructive pulmonary disease   | 18           | 1.48              | 0.88–2.34              | 16       | 0.99              | 0.56–1.60 | 1.20     | 0.83–1.67 |
| Other respiratory system                | <sup>a</sup> | 0.90              | 0.11–3.25              | 5        | 1.78              | 0.58–4.16 | 1.39     | 0.56–2.87 |
| Diseases of the digestive system        | 10           | 0.86              | 0.41–1.58              | 23       | 1.57              | 0.99–2.35 | 1.26     | 0.86–1.76 |
| Other digestive system                  | 5            | 0.76              | 0.25–1.77              | 15       | 1.45              | 0.81–2.39 | 1.18     | 0.72–1.82 |
| External causes of injury and poisoning | 24           | 1.95 <sup>b</sup> | 1.25–2.90              | 38       | 1.20              | 0.85–1.65 | 1.41     | 1.08–1.81 |
| Other accidents/adverse effects         | <sup>a</sup> | 1.52              | 0.56–3.31              | 12       | 1.33              | 0.69–2.32 | 1.39     | 0.82–2.19 |
| Motor vehicle accidents                 | 10           | 2.12 <sup>b</sup> | 1.02–3.89              | 10       | 0.90              | 0.43–1.65 | 1.26     | 0.77–1.95 |
| Suicide                                 | <sup>a</sup> | 2.35              | 0.76–5.48              | 12       | 1.52              | 0.79–2.66 | 1.70     | 0.99–2.72 |

1.00<sup>+</sup>, slightly > 1.00.

<sup>a</sup>For confidentiality, observed numbers of cases < 5 are not reported. <sup>b</sup>95% CI does not include 1.

In the studies of farmers, one correlate of the neuropsychologic symptoms was a tendency not to follow safety practices (Beseler and Stallones 2003), a pattern with implications for injury risks.

As for heart disease, oxidative chemical injury is thought to be important in atherogenesis, potentially implicating a wide range of chemicals (Ramos 1999). Exposure to carbon disulphide (Kristensen 1989; Lewis et al. 1999), methylmercury (Stern 2005), arsenic (Bunderson et al. 2004), and bis (2-chloroethoxy) methane (Dunnick et al. 2004) has been shown to cause atherogenesis or myocardial damage in human, *in vitro*, and/or animal studies. Additional evidence has come from research on the toxicology of fine airborne particulate matter, found to be associated with cardiovascular disease in epidemiologic studies (Nemmar et al. 2004).

The stressors at LC consisted of a series of events over months and years, starting with the first reports of chemical contamination and continuing through the responses of governmental agencies, different investigations, relocation, and its aftermath. Effects of stress in other communities near hazardous waste sites have included physiologic reactions that constitute risk factors for cardiovascular disease: elevated blood pressure, elevated levels

of stress hormones and catecholamines (Baum and Fleming 1993), demoralization (Horowitz and Stefanko 1989), and depression and anxiety (Foulks and McLellen 1992). Research supports the notion that at least a segment of the population reacts to stress with increased drinking (Holahan et al. 2001; Sillaber and Henniger 2004) or smoking (Carvajal et al. 2000; Kouvonen et al. 2005; Todd 2004). Alcohol consumption is a risk factor for injury outcomes, including suicide and motor vehicle crash injuries, whereas smoking is a risk factor for myocardial infarction and several cancers (Ezzati et al. 2002).

There was a significant excess risk of AMI for residents of tiers 1 and 2 during the closed period from 1954 to 1978 (Table 4). This may be a chance finding due to multiple comparisons, but it is consistent with the results of the external analyses using NYS as the standard. Interestingly, this excess risk was time dependent for men, disappearing by the end of the follow-up period. This finding suggests that the elevation in the risk of death from AMI, if real, was the result of acute and not chronic exposures or stressors. Several established risk factors for mortality, such as age, smoking, and male sex, were significantly associated with increased overall and cause-specific mortality, lending confidence to the overall design.

The study has several notable strengths. The cohort is well defined, with known residential locations and dates. Residents at the time of the evacuations were included, as well as persons who lived at LC before 1978. Exposures of 6 months to 39 years (median 8.5 years) were included, representing almost all areas of the EDA. Ninety-six percent of the cohort was successfully traced, minimizing an additional potential source of selection bias. We used two different, complementary research designs. One compared the cohort as a whole to two different standard populations; the other modeled potential internal differences in outcome associated with different exposures to the landfill while controlling for potential confounders. Mortality data obtained from death certificates avoid recall biases commonly associated with self-reported data. Although misclassification of the underlying cause of death may have occurred, such errors should be nondifferential with respect to exposure, attenuating rather than exaggerating any observed associations. Lastly, the study was conducted almost two decades after the crisis, allowing an adequate latency period to study chronic disease mortality.

Correspondingly, the study has several important limitations. By definition, the cohort is limited to residents who participated in interviews conducted in 1978–1982; not

**Table 4.** Cox proportional hazards modeling for mortality [HRs (95% CIs)], interviewees only ( $n = 3,796$ ).

| Variable                                          | All causes of death<br>( $n = 620$ ) | Neoplasms<br>( $n = 172$ )       | Circulatory system<br>( $n = 272$ ) | AMI <sup>a</sup><br>( $n = 116$ ) | Respiratory system<br>( $n = 49$ ) | External causes of injury and poison<br>( $n = 42$ ) |
|---------------------------------------------------|--------------------------------------|----------------------------------|-------------------------------------|-----------------------------------|------------------------------------|------------------------------------------------------|
| Open period, tier 1 or tier 2 (years)             | 0.98<br>(0.89–1.08)                  | 0.86<br>(0.64–1.16)              | 1.02<br>(0.92–1.15)                 | 1.01<br>(0.86–1.20)               | 1.13<br>(0.92–1.38)                | 0.89<br>(0.39–2.02)                                  |
| Open period, tier 3 or tier 4 (years)             | 0.99<br>(0.97–1.01)                  | 0.98<br>(0.94–1.02)              | 1.00<br>(0.97–1.03)                 | 0.98<br>(0.94–1.03)               | 0.99<br>(0.93–1.07)                | 1.02<br>(0.94–1.12)                                  |
| Closed period, tier 1 or tier 2 (years)           | 1.00<br>(0.98–1.01)                  | 1.01<br>(0.98–1.03)              | 1.00<br>(0.98–1.02)                 | 1.06 <sup>b</sup><br>(1.01–1.12)  | 0.98<br>(0.94–1.03)                | 0.97<br>(0.91–1.04)                                  |
| Closed period, tier 3 or tier 4 (years)           | 1.00<br>(0.99–1.01)                  | 1.00<br>(0.99–1.02)              | 1.00<br>(0.99–1.01)                 | 1.02<br>(1.00–1.03)               | 0.99<br>(0.96–1.02)                | 0.90 <sup>b</sup><br>(0.82–0.99)                     |
| Hot spot/swale (yes/no)                           | 0.91<br>(0.50–1.66)                  | 1.11<br>(0.41–3.02)              | 1.35<br>(0.63–2.89)                 | 0.83<br>(0.20–3.38)               | <sup>c</sup>                       | <sup>c</sup>                                         |
| Childhood exposure (yes/no)                       | 1.14<br>(0.54–2.42)                  | 2.50<br>(0.72–8.70)              | 0.98<br>(0.13–7.54)                 | 2.70<br>(0.33–21.12)              | <sup>c</sup><br>(0.16–2.91)        | 0.67                                                 |
| Years attending 99th Street School                | 0.96<br>(0.85–1.08)                  | 0.58<br>(0.33–1.04)              | 0.56<br>(0.24–1.29)                 | 0.52<br>(0.15–1.74)               | <sup>c</sup><br>(0.94–1.32)        | 1.12                                                 |
| Age (years)                                       | 1.10 <sup>b</sup><br>(1.09–1.10)     | 1.09 <sup>b</sup><br>(1.08–1.10) | 1.12 <sup>b</sup><br>(1.10–1.13)    | 1.11 <sup>b</sup><br>(1.09–1.13)  | 1.12 <sup>b</sup><br>(1.09–1.15)   | 1.01<br>(0.98–1.04)                                  |
| Sex (male)                                        | 1.65 <sup>b</sup><br>(1.36–2.02)     | 1.50 <sup>b</sup><br>(1.03–2.18) | 1.84 <sup>b</sup><br>(1.35–2.49)    | 4.28 <sup>b</sup><br>(1.79–10.21) | 1.24<br>(0.62–2.46)                | 1.72<br>(0.82–3.62)                                  |
| Ever smoked (yes/no)                              | 1.66 <sup>b</sup><br>(1.35–2.05)     | 1.63 <sup>b</sup><br>(1.10–2.44) | 1.36 <sup>b</sup><br>(1.00*–1.84)   | 1.34<br>(0.84–2.12)               | 6.23 <sup>b</sup><br>(2.15–18.02)  | 2.25<br>(0.93–5.45)                                  |
| Alcohol consumption (yes/no)                      | 0.91<br>(0.76–1.08)                  | 1.15<br>(0.81–1.63)              | 0.87<br>(0.67–1.13)                 | 0.80<br>(0.54–1.19)               | 1.65<br>(0.82–3.28)                | 1.16<br>(0.52–2.58)                                  |
| Potential occupational exposure to LCICs (yes/no) | 1.00<br>(0.83–1.21)                  | 1.01<br>(0.70–1.45)              | 1.24<br>(0.92–1.66)                 | 1.33<br>(0.85–2.11)               | 0.50 <sup>b</sup><br>(0.25–0.97)   | 0.94<br>(0.45–1.95)                                  |
| Interactions with survival time                   |                                      |                                  |                                     |                                   |                                    |                                                      |
| Closed period (tiers 1/2)                         |                                      |                                  |                                     | 0.99<br>(0.98–1.00)               |                                    |                                                      |
| Closed period (tiers 3/4)                         |                                      |                                  |                                     |                                   |                                    | 1.01<br>(1.00*–1.02)                                 |
| Sex                                               |                                      |                                  |                                     | 0.91<br>(0.85–0.99)               |                                    |                                                      |

1.00\*, slightly > 1.00; 1.00<sup>-</sup>, slightly < 1.00.

<sup>a</sup>AMI is a subset of circulatory diseases. <sup>b</sup>CI does not include 1.00. <sup>c</sup>HR not calculable because of zero cells.

all former residents were identified at that time. Consequently, deaths that occurred before 1978 were excluded, possibly biasing the results toward the null. Despite a total of nearly 100,000 person-years of follow-up, statistical power was low for many specific causes of death, especially in the internal analyses resulting in small numbers and imprecision. Thus, for the most part, analyses were limited to the organ system level. Similarly, the cohort is relatively young and may not yet be at elevated risk of many causes of death despite the median of 32 years from first residential exposure to the end of follow-up. In the exposure assessment we used data from a wide variety of sources; data were, of necessity, qualitative because environmental sampling data were unavailable before 1978. Thus, exposure misclassification may have occurred, obscuring possible associations. However, serum samples archived from 1978 were available for 373 persons in the cohort and are being analyzed for concentrations of selected LCICs. These data may help validate time and location of residence as exposure surrogates. Finally, mortality is a relatively crude indicator of the effect of environmental exposures. Future investigations will focus on cancer incidence and adverse reproductive outcomes, which may be more sensitive end points in this population.

## Conclusion

This study was conducted to help assess, for the first time, the long-term health effects of residence at LC, the site of one of the first and most seriously contaminated hazardous waste sites in the history of the United States. The results did not demonstrate an elevation of overall mortality in the LC cohort compared with Niagara County or NYS from 1979 to 1996. There was some evidence of higher than expected death rates from AMI compared with NYS and from external causes of injury, principally suicide and motor vehicle accidents, compared with both NYS and Niagara County. The finding of no elevation for AMI compared with Niagara County suggests possible regional differences. However, persons who lived in tiers 1 and 2 during the closed period (1954–1978) had a higher risk of death from AMI. The role of exposure to the LC landfill in explaining these excess risks is not clear given limitations such as multiple comparisons, a qualitative exposure assessment, an incomplete cohort, and no death data prior to 1978. However, either direct cardiotoxic and neurotoxic effects from landfill chemicals or indirect effects mediated by psychological stress cannot be ruled out. Because many analyses were limited by small numbers of deaths and because the study population is still relatively young (median age < 50 years in 1996), revisiting the cohort in the future could reveal patterns that are not yet apparent.

## CORRECTION

In the original article published online, the list of authors was incorrect. Syni-An Hwang has been included here.

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Review

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## Systematic review of epidemiological studies on health effects associated with management of solid waste

Daniela Porta<sup>1</sup>, Simona Milani<sup>1</sup>, Antonio I Lazzarino<sup>1,2</sup>, Carlo A Perucci<sup>1</sup> and Francesco Forastiere\*<sup>1</sup>

Address: <sup>1</sup>Department of Epidemiology, Regional Health Service Lazio Region, Rome, Italy and <sup>2</sup>Division of Epidemiology, Public Health and Primary Care, Imperial College, London, UK

Email: Daniela Porta - porta@asplazio.it; Simona Milani - milani@asplazio.it; Antonio I Lazzarino - a.lazzarino@imperial.ac.uk; Carlo A Perucci - perucci@asplazio.it; Francesco Forastiere\* - forastiere@asplazio.it

\* Corresponding author

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### Abstract

**Background:** Management of solid waste (mainly landfills and incineration) releases a number of toxic substances, most in small quantities and at extremely low levels. Because of the wide range of pollutants, the different pathways of exposure, long-term low-level exposure, and the potential for synergism among the pollutants, concerns remain about potential health effects but there are many uncertainties involved in the assessment. Our aim was to systematically review the available epidemiological literature on the health effects in the vicinity of landfills and incinerators and among workers at waste processing plants to derive usable excess risk estimates for health impact assessment.

**Methods:** We examined the published, peer-reviewed literature addressing health effects of waste management between 1983 and 2008. For each paper, we examined the study design and assessed potential biases in the effect estimates. We evaluated the overall evidence and graded the associated uncertainties.

**Results:** In most cases the overall evidence was inadequate to establish a relationship between a specific waste process and health effects; the evidence from occupational studies was not sufficient to make an overall assessment. For community studies, at least for some processes, there was limited evidence of a causal relationship and a few studies were selected for a quantitative evaluation. In particular, for populations living within two kilometres of landfills there was limited evidence of congenital anomalies and low birth weight with excess risk of 2 percent and 6 percent, respectively. The excess risk tended to be higher when sites dealing with toxic wastes were considered. For populations living within three kilometres of old incinerators, there was limited evidence of an increased risk of cancer, with an estimated excess risk of 3.5 percent. The confidence in the evaluation and in the estimated excess risk tended to be higher for specific cancer forms such as non-Hodgkin's lymphoma and soft tissue sarcoma than for other cancers.

**Conclusions:** The studies we have reviewed suffer from many limitations due to poor exposure assessment, ecological level of analysis, and lack of information on relevant confounders. With a moderate level confidence, however, we have derived some effect estimates that could be used for health impact assessment of old landfill and incineration plants. The uncertainties surrounding these numbers should be considered carefully when health effects are estimated. It is clear that future research into the health risks of waste management needs to overcome current limitations.

## Introduction

"Waste management", that is the generation, collection, processing, transport, and disposal of solid waste is important for both environmental reasons and public health. There are a number of different options available for the management and treatment of waste including minimisation, recycling, composting, energy recovery and disposal. At present, an increasing amount of the resources contained in waste is recycled, but a large portion is incinerated or permanently lost in landfills. The various methods of waste management release a number of substances, most in small quantities and at extremely low levels. However, concerns remain about potential health effects associated with the main waste management technologies and there are many uncertainties involved in the assessment of health effects.

Several studies of the possible health effects on populations living in proximity of landfills and incinerators have been published and well-conducted reviews are available [1-4]. Both landfills and incinerators have been associated with some reproductive and cancer outcomes. However, the reviews indicate the weakness of the results of the available studies due to design issues, mainly related to a lack of exposure information, use of indirect surrogate measures, such as the distance from the source, and lack of control for potential confounders. As a result, there is great controversy over the possible health effects of waste management on the public due to differences in risk communication, risk perception and the conflicting interests of various stakeholders. Therefore, there is the need for an appropriate risk assessment that informs both policy makers and the public with the information currently available on the health risks associated with different waste management technologies. Of course, the current uncertainties should be taken into account.

Within the EU-funded INTARESE project [5], we aimed to assess potential exposures and health effects arising from solid wastes, from generation to disposal, or treatment. A key part in the health impact assessment was selecting or developing a suitable set of relative risks that link individual exposures with specific health endpoints. In this paper, we systematically reviewed the available epidemiological literature on health effects in the vicinity of landfills and incinerators and among workers at waste processing plants to derive usable excess risk estimates for health impact assessment. The degree of uncertainty associated with these estimates was considered.

## Methods

We considered epidemiological studies conducted on the general population with potential exposures from collecting, recycling, composting, incinerating, and landfilling solid waste. We also considered studies of employees of

waste management plants as they may be exposed to the same potential hazards as the community residents, even if the intensity and duration of the exposure may differ. However, to limit our scope, we did not consider studies on biomarkers of exposure and health effects.

Relevant papers were found through computerized literature searches of MEDLINE and PubMed Databases from 1/1/1983 through 31/12/2008, using the MeSH terms "waste management" and "waste products" and the sub-heading "adverse effects". We identified 144 papers with this method. We also conducted a free search with several combinations of relevant key words (waste incinerator or landfill or composting or recycling) and (cancer or birth outcome or health effects), and 285 papers were identified. In addition, articles were traced through references listed in previous reviews [1-3,6-9], and in publications of the UK Department for Environment, Food and Rural Affairs [10]. Finally, we used information from two recent reviews of epidemiological studies on populations with potential exposures from toxic and hazardous wastes for reproductive [4], and cancer [11] outcomes, respectively.

The eligibility of all papers was evaluated independently by three observers, and disagreements were resolved by discussion. As indicated, studies on sewage treatment and on biological monitoring were not included. We also excluded articles in languages other than English, not journal articles, and six studies [12-17] conducted at the municipal level (usually small towns) where it was not possible to evaluate the extent of the population potentially involved and the possibility of exposure misclassification was high.

Papers were grouped according to the following criteria:

- waste management technologies: recycling, composting, incinerating, landfilling (considering controlled disposal of waste land and toxic or hazardous sites);
- health outcomes: cancers (stomach, colorectal, liver, larynx and lung cancer, soft tissue sarcoma, kidney and bladder cancer, non-Hodgkin's lymphoma, childhood cancer), birth outcomes (congenital malformations, low birth weight, multiple births, abnormal sex ratio of newborns), respiratory, skin and gastrointestinal symptoms or diseases.

We have reported in the appropriate tables (in the online additional files) for each paper: study design (e.g. geographical, cohort, cross-sectional, case-control study, etc.), population characteristics (subjects, country, age, sex), exposure measures (e.g. occupational exposure to waste incinerator by-products, residence near a landfill, etc.), and the main results (including control for major

confounders) with respect to the quantification of the health effects studied. For each study we have evaluated the potential sources of uncertainty in the results due to design issues. In particular, the possibility that selection bias, information bias, or confounding could artificially increase or decrease the relative risk estimate has been noted in the tables using the plus/minus scale to indicate that effect estimates are likely to be overestimated (or underestimated) up to 20% (+/-), from 20 to 50% (++) and more than 50% (+++/-). Uncertainties were graded by two observers (SM and FF), who discussed the inconsistencies.

After a description of the available studies, the overall evaluation of the epidemiological evidence regarding the process/disease association was made based on the IARC (1999) criteria, and two categories were chosen, namely: "Inadequate" when the available studies were of insufficient quality, consistency, or statistical power to determine the presence or absence of a causal association; "Limited" when a positive association was observed between exposure and disease for which a causal interpretation is considered to be credible, but chance, bias, or confounding could not be ruled out with reasonable confidence. There were no instances where the category "sufficient" evidence could be used. Only when the specific process/disease association was judged as limited (suggestive evidence but not sufficient to infer causality) we decided to evaluate the strength of the association and to measure appropriate relative risks. For this purpose, we considered the set of studies providing the best evidence and assigned an overall level of scientific confidence of the specific effect estimate based on an arbitrary scale: very high, high, moderate, low, very low. This evaluation was made by three assessors (SM, DP, and FF).

## Results

A total of 49 papers were reviewed: 32 concerning health effects in communities in proximity to waste sites, and 17 on employees of waste management sites. The majority of community studies evaluated possible adverse health effects in relation to incinerators and landfills. We found little evidence on potential health problems resulting from environmental or occupational exposures from composting or recycling, and very little on storage/collection of solid waste. A description of the main findings follows.

### Studies of communities near landfills

One of the main problems in dealing with studies on landfill sites (an to some extent also for incinerators) is the distinction between sites for municipal solid wastes and sites for other wastes. The definition of different types of waste is far from being standardised across the world. The terms hazardous, special, toxic, industrial, commer-

cial, etc, are variously applied in different countries and time periods to designate non-household wastes. In earlier time periods definitions were even less clear and some disposal sites may have switched categories (e.g. if they used to take industrial waste they may now only take municipal waste). Since two systematic reviews were already available for toxic wastes [4,11], we did not replicate the literature search, but summarized the evidence reported in the available reviews and tried to compare and discuss the results with studies where mainly municipal solid wastes were landfilled. The additional file 1 contain several details of the studies reviewed.

### Cancer

Russi et al. [11] carried out Medline searches of the peer-reviewed English language medical literature covering the period from January 1980 to June 2006 using the keywords "toxic sites" and "cancer", and identified articles from published reviews. They included 19 articles which fit the following selection criteria: 1) the study addressed either cancer incidence or cancer mortality as an endpoint, 2) the study was carried out in a community or a set of communities containing a known hazardous waste site; 3) the study had to address exposure from a specific waste site, rather than from a contaminated water supply resulted from multiple point sources. As the authors recognized, some of the location investigated included both toxic wastes and municipal solid wastes as in the study from Goldberg et al. [18] or Pukkala et al. [19]. There are two investigations considered in this review that are important to evaluate because of the originality of the approach (cohort study, [19] and due to the large size [20].

In Finland, Pukkala et al. [19] studied whether the exposure to landfills caused cancer or other chronic diseases in inhabitants of houses built on a former dumping area containing industrial and household wastes. After adjusting for age and sex, an excess number of male cancer cases were seen, especially for cancers of the pancreas and of the skin. The relative risk slightly increased with the number of years lived in the area. However, some uncertainties were likely to affect the results of the study with regards to the exposure assessment (-), outcome assessment (+) and presence of residual confounding (-).

Jarup et al. [20] examined cancer risks in populations living within 2 km of 9,565 (from a total of 19,196) landfill sites that were operational at some time from 1982 to 1997 in Great Britain. No excess risks of cancers of the bladder and brain, hepato-biliary cancer or leukaemia were found, after adjusting for age, sex, calendar year and deprivation. The study was very large and had high power, however misclassification of exposure could have decreased the possibility of detecting an effect (-).

Based on the findings and on the evaluation of the quality of the studies, Russi et al. [11] concluded that epidemiological studies of populations living in the vicinity of a toxic waste site have not produced evidence of adequate quality to establish a casual link between toxic waste exposures and cancer risk. In our terms, the evidence may be considered as "inadequate".

In addition to the articles reviewed by Russi et al. [11], we reviewed the article by Michelozzi et al. [21], which investigated the mortality risk in a small area of Italy (Malgrotta, Rome) with multiple sources of air contamination (a very large waste disposal site serving the entire city of Rome, a waste incinerator plant, and an oil refinery plant). Standardised Mortality Ratios (SMRs) were computed in bands of increasing distance from the plants, up to a radius of 10 km. No association was found between proximity to the sites and cancer of various organs, in particular liver, lung, and lymph haematopoietic cancer, however, mortality from laryngeal cancer declined with distance from the pollution sources, and a statistically significant trend remained after adjusting for a four-level index of socio-economic status. The main uncertainty of the study is related to the exposure assessment (--) since only distance was considered thus decreasing the possibility of detecting an effect. There are also uncertainties in using mortality to estimate cancer incidence in proximity to a suspected source of pollution (+). On the other hand, even though the authors did adjust for an area-based index of deprivation, residual confounding (+) from socioeconomic status was likely.

In summary, there is inadequate evidence of an increased risk of cancer for communities in proximity of landfills. The three slightly positive studies from Goldberg et al. [18], Pukkala et al. [19] and Michelozzi et al. [21] are not consistent.

#### **Birth defects and reproductive disorders**

Saunders [4] reviewed 29 papers examining the relationship between residential proximity to landfill sites and the risk of an adverse birth outcome. The review included either studies on municipal waste or on hazardous waste. Eighteen papers reported some significant association between adverse reproductive outcome and residence near a landfill site. Two of the strongest papers conducted on hazardous waste landfill sites in Europe (EUROHAZCON) found similarly moderate but significant associations between residential proximity (within 3 km) to hazardous waste sites and both chromosomal [22] (Odds Ratio, OR: 1.41, 95%CI: 1.00-1.99) and non-chromosomal [23] (OR: 1.33, 95%CI: 1.11-1.59) congenital anomalies.

Included in the Saunders's review [4] is the national geographical comparison study on landfills in the UK by Elliott et al. [24]. This study investigated the risk of adverse birth outcomes in populations living within two km of 9,565 landfill sites in Great Britain, operational at some time between 1982 and 1997, compared with those living further away (reference population). The sites included 774 sites for special (hazardous) waste, 7803 for non-special waste and 988 handling unknown waste; a two km zone was defined around each site to detect the likely limit of dispersion for landfill emissions, including 55% of the national population. Among the 8.2 million live births and 43,471 stillbirths, 124,597 congenital anomalies (including miscarriage) that were examined, there were: neural tube defects, cardiovascular defects, abdominal wall defects, hypospadias and epispadias, surgical correction of gastroschisis and exomphalos; low and very low birth weights were also found, defined as less than 2500 g and less than 1500 g, respectively. The main analysis, conducted for all landfill sites during their operation and after closure, found a small, but still statistically significant, increased risk of total and specific anomalies (OR: 1.01, 95%CI: 1.005-1.023) in populations living within 2 Km, and also an increased risk of low (OR: 1.05, 95%CI: 1.047-1.055) and very low birth weight (OR: 1.04, 95%CI: 1.03-1.05). Additional analyses were carried out separately for sites handling special waste and non-special waste, and in the period before and after opening, for the 5,260 landfills with available data. After adjusting for deprivation and other potential confounding variables (sex, year of birth, administrative region), there was a small increase in the relative risks for low and very low birth weight and for all congenital anomalies, except for cardiovascular defects. The risks of all congenital anomalies were higher for people living near special waste disposals (OR: 1.07 CI95%:1.04-1.09) compared to non-special waste disposals (OR: 1.02, CI95%:1.01-1.03). There was no excess risk of stillbirth. On these bases, the author [4] concluded that while most studies reporting a positive association are of good quality, over half report no association with any adverse birth outcome and most of the latter are also well conducted. The review considered that the evidence of an association of residence near a landfill with adverse birth outcomes as unconvincing.

After the review by Saunders [4], we considered four additional studies examining reproductive effects of landfill emissions.

Elliott et al. recently updated the previous study [25] in order to evaluate whether geographical density of landfill sites was related to congenital anomalies. The analysis was restricted to 8804 sites operational at some time between 1982 and 1997. There were 607 sites handling special (hazardous) waste and 8197 handling non-special or

unknown waste type. The exposure assessment took into account the overlap of the two km buffers around each site, to define an index of exposure with four levels of increasing landfill density. Several anomalies (hypospadias and epispadias, cardiovascular defects, neural tube defects and abdominal wall defects) were evaluated. The analysis was carried out separately for special and non-special waste sites and was adjusted for deprivation, presence or absence of a local congenital anomalies register and maternal age. The study found a weak association between intensity of hazardous sites and some congenital anomalies (all, cardiovascular, hypospadias and epispadias).

The studies conducted in the United Kingdom suffer from the same limitations, namely the possibility that misclassification of exposure could have decreased the relative risk estimates to some extent (--); on the other hand, there are several uncertainties related to the quality of reporting and registration of congenital malformations. In the latter case, a positive bias is more likely (++). For the recent report by Elliott et al. [25], location uncertainties and differential data reliability regarding the sites, together with the use of distance as the basis for exposure classification, limit the interpretation of the findings (--).

In Denmark, Kloppenborg et al. [26] marked the geographical location of 48 landfills and used maternal residence as the exposure indicator in a study of congenital malformations. The authors found no association between landfill location and all congenital anomalies or of the nervous system, and a small excess risk for congenital anomalies of the cardiovascular system. Potential confounding from socioeconomic status is the major limitation of this study (+++).

Jarup et al. [27] studied the risk of Down's syndrome in the population living near 6829 landfills in England and Wales. People were considered exposed if they lived in a two-km zone around each site, people beyond this zone were the reference group. A two-year lag period between potential exposure of the mother and her giving birth to a Down's syndrome child was allowed. The analysis was adjusted for maternal age, urban-rural status and deprivation index. No statistically significant excess risk was found in the exposed populations, regardless of waste type.

Finally, Gilbreath et al. [28] studied births in 197 Native Alaskan villages containing open dumpsites with hazardous waste, scoring the exposure into high, intermediate and low hazard level on the basis of maternal residence. The authors found an association between higher levels of hazard and low birth weight and intrauterine growth

retardation. The major limit of the study is the low specificity of the exposure definition.

In summary, an increased risk of congenital malformations and of low birth weight has been reported from studies conducted in the UK. When compared with the results from studies conducted in proximity of hazardous waste sites, studies in proximity of non-toxic waste landfills provide lower effect estimates. The main uncertainty of these studies is the completeness of data on birth defects, the use of distance from the sites for exposure classification, and the classification as toxic and non-toxic waste sites.

### **Respiratory diseases**

A study conducted by Pukkala et al. [19] in Finland evaluated prevalence of asthma in relation to residence in houses built on a former dumping area containing industrial and household wastes. Prevalence of asthma was significantly higher in the dump cohort than in the reference cohort (living nearby but outside the landfill site). Unfortunately, this study has not been replicated and the overall evidence may be considered inadequate.

### **Studies of landfills workers**

Only one study on landfill workers was reviewed. Gelberg et al. [29] conducted a cross-sectional study to examine acute health effects among employees working for the New York City Department of Sanitation, focusing on Fresh Kills landfill employees. Telephone interviews conducted with 238 on-site and 262 off-site male employees asked about potential exposures both at home and work, health symptoms for the previous six months, and other information (social and recreational habits, socioeconomic status). Landfill workers reported a significantly higher prevalence of work-related respiratory, dermatological, neurologic and hearing problems than controls. Respiratory and dermatologic symptoms were not associated with any specific occupational title or task, other than working at the landfill, and the association remained, even after controlling for smoking status.

### **Studies of communities living near incinerators**

Twenty-one epidemiologic studies conducted on residents of communities with solid waste incinerators have been reviewed and their characteristics are listed in the additional file 2.

### **Cancer**

Eleven studies have been reviewed on cancer risk in relation with incinerators, usually old plants with high polluting characteristics. The studies are reported below by country.

In the United Kingdom, Elliott et al. [30] investigated cancer incidence between 1974 and 1987 among over 14 million people living near 72 solid waste incinerator plants. Data on cancer incidence among the residents, obtained from the national cancer registration programme, were compared with national cancer rates, and numbers of observed and expected cases were calculated after stratifying for deprivation, based on the 1981 census. Observed-expected ratios were tested for decline in risk up to 7.5 km away. The study was conducted in two stages: the first involved a stratified random sample of 20 incinerators and, based on the findings, a number of cancers were then further studied around the remaining 52 incinerators (second stage). Over the two stages of the study there was a statistically significant ( $p < 0.05$ ) decline in risk with distance from incinerators for all cancers, stomach, colorectal, liver and lung cancer. The use of distance as the exposure variable in this study could have led to some degree of misclassification (--). On the other hand, the same authors observed that residual confounding (+) as well as misdiagnosis (+) might have increased the risk estimates. When further analyses were made, including a histological review of liver cancer cases [31], the risk estimates were lower (0.53-0.78 excess cases per  $10^5$  per year within 1 km, instead of 0.95 excess cases per  $10^5$  as previously estimated).

Using data on municipal solid waste incinerators from the initial study by Elliott et al. [30], Knox [32] examined a possible association between childhood cancers and industrial emissions, including those from incinerators. From a database of 22,458 cancer deaths that occurred in children before their 16<sup>th</sup> birthday between 1953 and 1980, he extracted 9,224 cases known to have moved at least 0.1 km in their life time, and using a newly developed technique of analysis, he compared distances from the suspected sources to the birth addresses and to the death addresses. The childhood-cancer/leukaemia data showed highly significant excesses of moves away from birthplaces close to municipal incinerators, but the specific effects of the municipal incinerators could not be separated clearly from those of nearby industrial sources of combustion. Misclassification of exposure is the main limit of this paper (--).

In France, Viel et al. [33] detected a cluster of patients with non-Hodgkin's lymphoma (NHL) and soft tissue sarcoma around a French municipal solid waste incinerator with high dioxin emissions. To better explore the environmental origin of the cluster suggested by these findings, Floret et al. [34] carried out a population-based case-control study in the same area, comparing 222 incident cases of NHL diagnosed between 1980 and 1995 and controls randomly selected from the 1990 census. The risk of developing lymphomas was 2.3 times higher among individuals

living in the area with the highest dioxin concentration than among those in the area with the lowest concentration. Given that a model was used to attribute exposure to cases and controls, a random misclassification could have reduced the effect estimates (--). Based on these results, a nationwide study on NHL was conducted [35]. A total of 13 incinerators in France were investigated and dispersion modelling was used to estimate ground-level dioxin concentration. Information about the exposure levels and potential confounders was available at the census block level. A positive association between dioxin level and NHL was found with a stronger effect among females. Although the study represents an improvement regarding exposure assessment compared to investigations based on distance from the source, it should be noted that the analysis was conducted at the census block level and the possibility of misclassification of the exposure (-) as well as of residual confounding from socioeconomic status (+) remains.

Viel et al. [36] have recently reported the findings from a case-control study on breast cancer. There was no association or even a negative association between exposure to dioxin and breast cancer in women younger or older than 60 years, respectively, living near a French municipal solid waste incinerator with high exposure to dioxin. Design issues and residual confounding from age and other factors (---) limit the interpretations of the study.

In Italy, Biggeri et al. [37] conducted a case-control study in Trieste to investigate the relationship between multiple sources of environmental pollution and lung cancer. Based on distance from the sources, spatial models were used to evaluate the risk gradients and the directional effects separately for each source, after adjusting for age, smoking habits, likelihood of exposure to occupational carcinogens, and levels of air particulate. The results showed that the risk of lung cancer was inversely related to the distance from the incinerator, with a high excess relative risk very near the source and a very steep decrease moving away from it. The main problem of the study is the difficulty to separate the effects of other sources of pollution based on distance, and the possibility of potential confounding from other sources remains (++). An excess risk of lung cancer was also found in females living in two areas of the province of La Spezia (Italy) exposed to environmental pollution emitted by multiple sources, including an industrial waste incinerator [38]. Again in this study the limited exposure assessment could have decreased the risk estimates (--), but positive confounding from other sources is very likely.

A case-control study by Comba et al. [39] showed a significant increase in risk of soft tissue sarcomas associated with residence within two km of an industrial waste incin-

erator in the city of Mantua, with a rapid decrease in risk at greater distances. There is a slight likelihood that increased attention to the diagnosis for this form of cancer in the vicinity of the plant could have introduced a small bias (+) in the risk estimate. Another case-control study, carried out in the province of Venice by Zambon et al. [40] analyzed the association between soft-tissue sarcoma and exposure to dioxin in a large area with 10 municipal solid waste incinerators. The authors found a statistically significant increase in the risk of sarcoma in relation to both the level and the length of environmental modelled exposure to dioxin-like substances. The results were more significant for women than for men.

In summary, although several uncertainties limit the overall interpretation of the findings, there is limited evidence that people living in proximity of an incinerator have increased risk of all cancers, stomach, colon, liver, lung cancers based on the studies of Elliott et al. [30]. Specific studies on incinerators in France and in Italy suggest an increased risk for non-Hodgkin's lymphoma, and soft-tissue sarcoma.

#### **Birth defects and reproductive disorders**

Six studies examined reproductive effects of incinerator emissions (see additional file 2).

Jansson et al. [41] analysed whether the incidence of cleft lip and palate in Sweden increased since operation of a refuse incineration plant began. The results of this register study, based on information from the central register of malformations and the medical birth register, did not demonstrate an increased risk.

A study by Lloyd et al. [42] examined the incidence of twin births between 1975 and 1983 in two areas near a chemical and a municipal waste incinerator in Scotland: after adjusting for maternal age, an increased frequency of twinning in areas exposed to air pollution from incinerators was seen. In the same study areas, Williams et al. [43] investigated gender ratios, at various levels of geographical detail and using three-dimensional mapping techniques: analyses in the residential areas at risk from airborne pollution from incinerators showed locations with statistically significant excesses of female births.

To investigate the risk of stillbirth, neonatal death, and lethal congenital anomaly among infants of mothers living close to incinerators (and crematoriums), Dummer et al. [44] conducted a geographical study in Cumbria (Great Britain). After adjusting for social class, year of birth, birth order, and multiple births, there was an increased risk of lethal congenital anomaly, in particular spina bifida and heart defects.

Subsequently, Cordier et al. [45] studied communities with fewer than 50,000 inhabitants surrounding the 70 incinerators that operated for at least one year from 1988 to 1997 in France. Each exposed community was assigned an exposure index based on a Gaussian plume model, estimating concentrations of pollutants per number of years the plant had operated. The results were adjusted for year of birth, maternal age, department of birth, population density, average family income, and when available, local road traffic. The rate of congenital anomalies was not significantly higher in exposed compared with unexposed communities; only some subgroups of congenital anomalies, specifically facial cleft and renal dysplasia, were more frequent in the exposed communities.

Tango et al. [46] investigated the association of adverse reproductive outcomes with mothers living within 10 km of 63 municipal solid waste incinerators with high dioxin emission levels (above 80 ng international toxic equivalents TEQ/m<sup>3</sup>) in Japan. To calculate the expected number of cases, national rates based on all live births, fetal deaths and infant deaths occurred in the study area during 1997-1998 were used and stratified by potential confounding factors available from the corresponding vital statistics records: maternal age, gestational age, birth weight, total previous deliveries, past experience of fetal deaths, and type of paternal occupation. None of the reproductive outcomes studied showed statistically significant excess within two km of the incinerators, but a statistically significant decline in risk with distance from the incinerators was found for infant deaths and for infant deaths with congenital anomalies, probably due to dioxin emissions from the plants.

In sum, there are multiple reports of increased risk of congenital malformations among people living close to incinerators but there are no consistencies between the investigated outcomes. The overall evidence may be considered as limited. The study by Cordier et al. [45] provides the basis for risk quantifications at least for facial cleft and renal dysplasia. Quantification for other reproductive disorders is more difficult.

#### **Respiratory and skin diseases or symptoms**

Four studies examined respiratory and/or dermatologic effects of incinerator emissions (see additional file 2).

Hsiue et al. [47] evaluated the effect of long-term air pollution resulting from wire reclamation incineration on respiratory health in children. 382 primary school children who resided in one control and three polluted areas in Taiwan were chosen for this study. The results revealed a decrement in pulmonary function (including forced vital capacity and forced expiratory volume in one second) of those residents in the vicinity of incineration sites.

Shy et al. [48] studied the residents of three communities having, respectively, a biomedical and a municipal incinerator, and a liquid hazardous waste-burning industrial furnace, and then compared results with three matched-comparison communities. After adjustment for several confounders (age, sex, race, education, respiratory disease risk factors), no consistent differences in the prevalence of chronic or acute respiratory symptoms resulted between incinerator and comparison communities. Additionally, no changes in pulmonary function between subjects of an incinerator community and those of its comparison community resulted from the study by Lee et al. [49], based on a longitudinal component from the Health and Clean Air study by Shy et al. [48].

Miyake et al. [50] examined the relationship between the prevalence of allergic disorders and general symptoms in Japanese children and the distance of schools from incineration plants, measured using geographical information systems. After adjusting for grade, socio-economic status and access to health care per municipality, schools closer to the nearest municipal waste incineration plant were associated with an increased prevalence of wheeze and headache; there was no evident relationship between the distance of schools from such plants and the prevalence of atopic dermatitis. The main factors that may have affected the relative risk estimates in this study could be reporting bias (++) and residual confounding from socioeconomic status (++).

In sum, although the intensive study conducted by Shy et al. [48] did not show respiratory effects, there are some indications of an increased risk of respiratory diseases, especially in children. However, the uncertainty related to outcome assessment and residual confounding is very high and the overall evidence may be considered inadequate.

### **Occupational studies on incinerator employees**

Four studies conducted on incinerator employees were reviewed (see additional file 3).

In 1997, Rapiti et al. [51] conducted a retrospective mortality study on 532 male workers employed at two municipal waste incinerators in Rome (Italy) between 1962 and 1992. Standardized mortality ratios (SMRs) were computed using regional population mortality rates. Mortality from all causes resulted significantly lower than expected, and all cancer mortality was comparable with that of the general population. Mortality from lung cancer was lower than expected, but an increased risk was found for stomach cancer: analysis by latency since first exposure indicated that this excess risk was confined to the category of workers with more than 10 years since first exposure.

Bresnitz et al. [52] studied 89 of 105 male incinerator workers in Philadelphia, employed at the time of the study in late June 1988. Based on a work site analysis, workers were divided into potentially high and low exposure groups, and no statistically significant differences in pulmonary function were found between the two groups, after adjusting for smoking status.

A similar study was conducted by Hours et al. [53]: they analysed 102 male workers employed by three French urban incinerators during 1996, matched for age with 94 male workers from other industrial activities. The exposed workers were distributed into 3 exposure categories based on air sampling at the workplace: crane and equipment operators, furnace workers, and maintenance and effluent-treatment workers. An excess of respiratory problems, mainly daily cough, was more often found in the exposed groups, and a significant relationship between exposure and decreases in several pulmonary parameters was also observed, after adjusting for tobacco consumption and centre. The maintenance and effluent group, and the furnace group had elevated relative risks for skin symptoms.

In the same year, Takata et al. [54] conducted a cross-sectional study in Japan on 92 workers from a municipal solid waste incinerator to investigate the health effects of chronic exposure to dioxins. The concentrations of these chemicals among the blood of the workers who had engaged in maintenance of the furnace, electric dust collection, and the wet scrubber of the incinerator were higher compared with those of residents in surrounding areas, but there were no clinical signs or findings correlated to blood levels of dioxins.

In sum, there are some studies that suggest increased gastric cancer and respiratory problems among incinerators workers. However, there are a great number of uncertainties, which make it difficult to derive conclusions.

### **Epidemiological studies of health effects of other waste management processes**

Twelve epidemiologic studies on the potential adverse health effects of other waste management practices are reviewed and listed in additional file 4.

#### **Waste collection**

Ivens et al. [55] investigated the adverse health effects among waste collectors in Denmark. In a questionnaire-based survey among 2303 waste collectors and a comparison group of 1430 male municipal workers, information on self-reported health status and working conditions was collected and related to estimated bioaerosol exposure. After adjusting for several confounders (average alcohol consumption per day, smoking status, and the psychosocial exposure measures support/demand ), a dose-

response relationship between level of exposure to fungal spores and self-reported diarrhoea was indicated, meaning that the higher the weekly dose, the more reports of gastrointestinal symptoms.

In contrast with these results, a study of 853 workers employed by 27 municipal household waste collection departments in Taiwan did not find an excess of gastrointestinal symptoms [56]. The workers answered a questionnaire and were classified into two occupational groups by specific exposures based on the reported designation of their specific task. The exposed group included those working in the collection of mixed domestic waste, front runner or loader, collection of separated waste and special kinds of domestic waste (paper, glass, etc.), garden waste, bulky waste for incineration, and the vehicle driver; the control group included accountants, timekeepers, canteen staff, personnel, and other office workers. No significant differences were found in the prevalence of gastrointestinal symptoms, but results indicated that all respiratory symptom prevalence, except dyspnoea, were significantly higher in the exposed group, after adjusting for age, gender, education, smoking status, and duration of employment.

#### **Composting facilities**

In a German cross sectional study by Bünger et al. [57], work related health complaints and diseases of 58 compost workers and 53 bio-waste collectors were investigated and compared with 40 control subjects. Compost workers had significantly more symptoms and diseases of the skin and the airways than the control subjects. No correction was performed for the confounding effect of smoking, as there were no significant differences in the smoking habits of the three groups.

A subsequent study in Germany by Herr et al. [58] examined the health effects on community residents of bio-aerosol, emitted by a composting plant. A total of 356 questionnaires from residents living at different distances from the composting site, and from unexposed controls were collected: self-reported prevalence of health complaints over past years, doctors' diagnoses, as was residential odor annoyance; microbiological pollution was measured simultaneously in residential outdoor air. Reports of airway irritation were associated with residency in the highest bio-aerosol exposure category, 150-200 m (versus residency >400-500 m) from the site, and periods of residency more than five years.

Bünger et al. [59] conducted a prospective cohort study to investigate, in 41 plants in Germany, the health risks of compost workers due to long term exposure to organic dust that specifically focused on respiratory disorders. Employees, exposed and not exposed to organic dust,

were interviewed about respiratory symptoms and diseases in the last 12 months and had a spirometry after a 5-year follow-up. Exposure assessment was conducted at 6 out of 41 composting plants and at the individual level. Eyes, airways and skin symptoms were higher in compost workers than in the control group. There was also a steeper decline of Forced Vital Capacity among compost workers compared to control subjects, also when smoking was considered.

#### **Materials recycling facilities**

There are no epidemiological studies of populations living near materials recycling facilities; only studies on employees are available.

In the already-quoted study by Rapiti et al. [51] on workers at two municipal plants for incinerating and garbage recycling, increased risk was found for stomach cancer in employees who had worked there for at least 10 years, while lung cancer mortality risk was lower than expected.

In the study by Rix et al. [60], 5377 employees of five paper recycling plants in Denmark between 1965 and 1990 were included in a historical cohort, and the expected number of cancer cases was calculated from national rates. The incidence of lung cancer was slightly higher among men in production and moderately higher in short term workers with less than 1 year of employment; there was significantly more pharyngeal cancer among males, but this may have been influenced by confounders such as smoking and alcohol intake.

Sigsgaard et al. [61] conducted a cross-sectional study to examine the effect of shift changes on lung function among 99 recycling workers (resource recovery and paper mill workers), and correlated these findings with measurements of total dust and endotoxins. Exposure to organic dust caused a fall in FEV<sub>1</sub> over the work shift, and this was significantly associated with exposure to organic dust; no significant association was found between endotoxin exposure and lung function decreases.

The same authors [62] also analysed skin and gastrointestinal symptoms among 40 garbage handlers, 8 composters and 20 paper sorters from all over Denmark, and found that garbage handlers had an increased risk of skin itching, and vomiting or diarrhoea.

In a nationwide study, Ivens et al. [63] reported findings of self-reported gastrointestinal symptoms by self-reported type of plant. A questionnaire based survey among Danish waste recycling workers at all composting, biogas-producing, and sorting plants collected data on occupational exposures (including questions on type of plant, type of waste), present and past work environment,

the psychosocial work environment, and health status. Prevalence rate ratios adjusted for other possible types of job and relevant confounders were estimated with a comparison group of non-exposed workers, and an association was found between sorting paper and diarrhoea, between nausea and work at plastic sorting plants, and non-significantly between diarrhoea and work at composting plants.

The health status of workers employed in the paper recycling industry was also studied by Zuskin et al. [64]. A group of 101 male paper-recycling workers employed by one paper processing plant in Croatia, and a group of 87 non-exposed workers employed in the food packing industry was studied for the prevalence of chronic respiratory symptoms, and results indicated significantly higher prevalence of all chronic respiratory symptoms were found in paper workers compared with controls.

Gladding et al. [65] studied 159 workers from nine materials recovery facilities (MRFs) in the United Kingdom. Total airborne dust, endotoxins, (1-3)-beta-D-glucan were measured, and a questionnaire-survey was completed. The results suggest that materials recovery facilities workers exposed to higher levels of endotoxins and (1-3)-beta-D-glucan at their work sites experience various work-related symptoms, and that the longer a worker is in the MRF environment, the more likely he is to become

affected by various respiratory and gastrointestinal symptoms.

### Choosing relative risk estimates for health impact assessment of residence near landfills and incinerators

The reviewed studies have been used to summarize the evidence available, as indicated in table 1. When the overall degree of evidence was considered "inadequate" we decided not to propose a quantitative evaluation of the relative risk; when we arrived to a conclusion that "limited" evidence was available, relative risk estimates were extracted for use in the health impact assessment process. Table 2 summarizes the relevant and reliable figures for health effects related to landfills and incinerators. For each relative risk the distance from the source has been reported as well as the overall level of confidence of the effect estimates based on an arbitrary scale: very high, high, moderate, low, very low.

#### Landfills

From the review presented above and following the work already made by Russi et al. [11], it is clear that the studies on cancer are not sufficient to draw conclusions regarding health effects near landfills, both with toxic and non-toxic wastes. The largest study conducted in England by Jarup et al. [21] does not suggest an increase in the cancer types that were investigated. Investigations of other chronic dis-

**Table 1: Summary of the overall epidemiologic evidence on municipal solid waste disposal: landfills and incinerators.**

| HEALTH EFFECT                    | LEVEL OF EVIDENCE |              |
|----------------------------------|-------------------|--------------|
|                                  | LANDFILLS         | INCINERATORS |
| All cancer                       | Inadequate        | Limited      |
| Stomach cancer                   | Inadequate        | Limited      |
| Colorectal cancer                | Inadequate        | Limited      |
| Liver cancer                     | Inadequate        | Limited      |
| Larynx cancer                    | Inadequate        | Inadequate   |
| Lung cancer                      | Inadequate        | Limited      |
| Soft tissue sarcoma              | Inadequate        | Limited      |
| Kidney cancer                    | Inadequate        | Inadequate   |
| Bladder cancer                   | Inadequate        | Inadequate   |
| Non Hodgkin's lymphoma           | Inadequate        | Limited      |
| Childhood cancer                 | Inadequate        | Inadequate   |
| Total birth defects              | Limited           | Inadequate   |
| Neural tube defects              | Limited           | Inadequate   |
| Orofacial birth defects          | Inadequate        | Limited      |
| Genitourinary birth defects      | Limited*          | Limited**    |
| Abdominal wall defects           | Inadequate        | Inadequate   |
| Gastrointestinal birth defects§  | Inadequate        | Inadequate   |
| Low birth weight                 | Limited           | Inadequate   |
| Respiratory diseases or symptoms | Inadequate        | Inadequate   |

"Inadequate": available studies are of insufficient quality, consistency, or statistical power to decide the presence or absence of a causal association.

"Limited": a positive association has been observed between exposure and disease for which a causal interpretation is considered to be credible, but chance, bias, or confounding could not be ruled out with reasonable confidence.

\* Hypospadias and epispadias

\*\* Renal dysplasia

§ The original estimates were given for "surgical corrections of gastroschisis and exomphalos"

**Table 2: Relative risk estimates for community exposure to landfills and incinerators**

| Health effect                        | Distance from the source | Relative Risk (Confidence Interval) | Level of confidence** |
|--------------------------------------|--------------------------|-------------------------------------|-----------------------|
| <b>Landfills</b>                     |                          |                                     |                       |
| <b>Congenital malformations [24]</b> |                          |                                     |                       |
| All congenital malformations         | Within 2 km              | 1.02 (99% CI = 1.01-1.03)           | Moderate              |
| Neural tube defects                  | Within 2 km              | 1.06 (99% CI = 1.01-1.12)           | Moderate              |
| Hypospadias and epispadias           | Within 2 km              | 1.07 (99% CI = 1.04-1.11)           | Moderate              |
| Abdominal wall defects               | Within 2 km              | 1.05 (99% CI = 0.94-1.16)           | Moderate              |
| Gastroschisis and exomphalos*        | Within 2 km              | 1.18 (99% CI = 1.03-1.34)           | Moderate              |
| <b>Low birth weight [24]</b>         |                          |                                     |                       |
| Very low birth weight                | Within 2 km              | 1.06 (99% CI = 1.052-1.062)         | High                  |
|                                      | Within 2 km              | 1.04 (99% CI = 1.03-1.06)           | High                  |
| <b>Incinerators</b>                  |                          |                                     |                       |
| <b>Congenital malformations [45]</b> |                          |                                     |                       |
| Facial cleft                         | Within 10 km             | 1.30 (95% CI = 1.06-1.59)           | Moderate              |
| Renal dysplasia                      | Within 10 km             | 1.55 (95% CI = 1.10-2.20)           | Moderate              |
| <b>Cancer [30]</b>                   |                          |                                     |                       |
| All cancer                           | Within 3 km              | 1.035 (95% CI = 1.03-1.04)          | Moderate              |
| Stomach cancer                       | Within 3 km              | 1.07 (95% CI = 1.02-1.13)           | Moderate              |
| Colorectal cancer                    | Within 3 km              | 1.11 (95% CI = 1.07-1.15)           | Moderate              |
| Liver cancer                         | Within 3 km              | 1.29 (95% CI = 1.10-1.51)           | High                  |
| Lung cancer                          | Within 3 km              | 1.14 (95% CI = 1.11-1.17)           | Moderate              |
| Soft-tissue sarcoma                  | Within 3 km              | 1.16 (95% CI = 0.96-1.41)           | High                  |
| Non-Hodgkin's lymphoma               | Within 3 km              | 1.11 (95% CI = 1.04-1.19)           | High                  |

\*The original estimates were given for "surgical corrections of...". \*\*The following scale for the level of confidence has been adopted: very high, high, moderate, low, very low.

eases are lacking, especially of respiratory diseases, yet there is one indication of an increased risk of asthma in adults [19], but with no replication of the findings. Overall, the evidence that living near landfills may be associated with health effects in adults is inadequate.

A slightly different picture appears for congenital malformations and low birth weight, where limited evidence exists of an increased risk for infants born to mothers living near landfill sites. The relevant results come from the European EUROHAZCON Study [23] and the national investigation from Elliott et al. [24]. In the UK report, statistically significant higher risk were found for all congenital malformations, neural tube defects, abdominal wall defects, surgical correction of gastroschisis and exomphalos, and low and very low birth weight for births to people living within two km of the sites, both of hazardous and non-hazardous waste. Although several alternative explanations, including ascertainment bias, and residual confounding cannot be excluded in the study, Elliott et al. [24] provide quantitative effect estimates whose level of confidence can be considered as moderate.

### Incinerators

Quantitative estimates of excess risk of specific cancers in populations living near solid waste incinerator plants were provided by Elliott et al. [30]. We have reported in table 2 the effect estimates for all cancers, stomach, colon, liver, and lung cancer based on their "second stage" analysis. There was an indication of residual confounding

from socioeconomic status near the incinerators and a concern of misdiagnosis among registrations and death certificates for liver cancer. The histology of the liver cancer cases was reviewed, re-estimating the previously calculated excess risk (from 0.95 excess cases 10<sup>-5</sup>/year to between 0.53 and 0.78 excess cases 10<sup>-5</sup>/year). We then graded the confidence of the assessment for these tumours as "moderate" with the exception of liver cancer (high) since the misdiagnosis was reassessed and the extent of residual confounding was lower. In the study by Elliott et al. [30] no significant decline in risk with distance for non-Hodgkin's lymphoma and soft tissue sarcoma was found. However, the studies of Viel et al. [33] and Floret et al. [34] conducted in France and the studies from Comba et al. [39] and Zambon et al. [40] in Italy provide some indications that an excess of these forms of cancers may be related to emissions of dioxins from incinerators. As a result, we provided effect estimates in table 2 also for non-Hodgkin's lymphoma and soft tissue sarcoma as derived from the conservative "first stage" analysis conducted by Elliott et al. [30]. We graded the level of confidence of these relative risk estimates as "high".

With regards to congenital malformations near incinerators, Cordier et al. [45] provided effect estimates for facial cleft and renal dysplasia, as they were more frequent in the "exposed" communities living within 10 km of the sites. Other reproductive effects, such as an effect on twinning rates or gender determination, have been described; however the results are inadequate.

## Conclusions

We have conducted a systematic review of the literature regarding the health effects of waste management. After the extensive review, in many cases the overall evidence was inadequate to establish a relationship between a specific waste process and health effects. However, at least for some associations, a limited amount of evidence has been found and a few studies were selected for a quantitative evaluation of the health effects. These relative risks could be used to assess health impact, considering that the level of confidence in these effect estimates is at least moderate for most of them.

Most of the reviewed studies suffer from limitations related to poor exposure assessment, aggregate level of analysis, and lack of information on relevant confounders. It is clear that future research into the health risks of waste management requires a more accurate characterization of individual exposure, improved knowledge of chemical and toxicological data on specific compounds, multi-site studies on large populations to increase statistical power, approaches based on individuals rather than communities and better control of confounding factors.

## List of abbreviations used

EU: European Union; INTARESE: Integrated Assessment of Health Risks of Environmental Stressors in Europe; NHL: non-Hodgkin's Lymphoma; OR: Odds ratio; TEQ: Toxic Equivalent.

## Competing interests

The authors declare that they have no competing interests.

## Authors' contributions

DP participated in the design of the study, conducted the systematic review and drafted the manuscript. SM conducted the systematic review and contributed to draft the manuscript. AIL participated in the systematic review and contributed to draft the manuscript. CAP helped to conceive of the study and to write and revise the manuscript. FF conceived and coordinated the study and helped to write and revise the manuscript. All authors have read and approved the final manuscript.

## Additional material

### Additional file 1

*Studies on landfills. The data provided represent a brief description of the studies on populations living near landfills.*

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### Additional file 2

*Studies on incinerators. The data provided represent a brief description of the studies on populations living near incinerators.*

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### Additional file 3

*Studies on occupational exposures among incinerators and landfills workers. The data provided represent a brief description of the studies on workers of waste management plants.*

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### Additional file 4

*Studies on other waste management processes. The data provided represent a brief description of the studies on population living near plants using waste management technologies different from landfills and incinerators.*

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# An overview of the environmental pollution and health effects associated with waste landfilling and open dumping

Ayesha Siddiqua<sup>2</sup> · John N. Hahladakis<sup>1</sup> · Wadha Ahmed K A Al-Attiya<sup>2</sup>

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## Abstract

Landfilling is one of the most common waste management methods employed in all countries alike, irrespective of their developmental status. The most commonly used types of landfills are (a) municipal solid waste landfill, (b) industrial waste landfill, and (c) hazardous waste landfill. There is, also, an emerging landfill type called “green waste landfill” that is, occasionally, being used. Most landfills, including those discussed in this review article, are controlled and engineered establishments, wherein the waste ought to abide with certain regulations regarding their quality and quantity. However, illegal and uncontrolled “landfills” (mostly known as open dumpsites) are, unfortunately, prevalent in many developing countries. Due to the widespread use of landfilling, even as of today, it is imperative to examine any environmental- and/or health-related issues that have emerged. The present study seeks to determine the environmental pollution and health effects associated with waste landfilling by adopting a desk review design. It is revealed that landfilling is associated with various environmental pollution problems, namely, (a) underground water pollution due to the leaching of organic, inorganic, and various other substances of concern (SoC) contained in the waste, (b) air pollution due to suspension of particles, (c) odor pollution from the deposition of municipal solid waste (MSW), and (d) even marine pollution from any potential run-offs. Furthermore, health impacts may occur through the pollution of the underground water and the emissions of gases, leading to carcinogenic and non-carcinogenic effects of the exposed population living in their vicinity.

**Keywords** Waste landfilling · Solid waste · Environmental pollution · Health effects · Landfill · Waste management

## Highlights

- Landfilling is still the predominant waste management option in many countries.
- Open dumping entails numerous environmental and, more importantly, health risks.
- Even a controlled landfill may pose environmental and human health implications.
- As per the waste hierarchy, landfilling should be the final waste management option.
- Open burning/dumping should be eliminated, and open dumpsites should close.

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✉ John N. Hahladakis  
john\_chach@yahoo.gr; ichachladakis@qu.edu.qa

<sup>1</sup> Waste Management (FEWS) Program, Center for Sustainable Development, College of Arts and Science, Qatar University, P.O. Box 2713, Doha, Qatar

<sup>2</sup> Department of Environmental and Biological Sciences, College of Arts and Science, Qatar University, P.O. Box 2713, Doha, Qatar

## Nomenclature

|        |                                      |
|--------|--------------------------------------|
| CBR    | California bearing ratio             |
| EC     | Electrical conductivity              |
| EDC    | Endocrine-disrupting compounds       |
| GHG    | Greenhouse gases                     |
| ISQG   | Interim sediment quality guidelines  |
| LFG    | Landfill gas                         |
| LWPI   | Landfill water pollution index       |
| MPs    | Microplastics                        |
| MSW    | Municipal solid waste                |
| NCDs   | Non-communicable diseases            |
| PBDEs  | Polybrominated diphenyl ethers       |
| PCBs   | Polychlorinated biphenyls            |
| PCDFs  | Polychlorinated dibenzofurans        |
| POPs   | Persistent organic pollutants        |
| PTEs   | Potentially toxic elements           |
| SoC    | Substances of concern                |
| TDS    | Total dissolved solids               |
| UNEP   | United Nations Environment Programme |
| US EPA | US Environmental Protection Agency   |
| USA    | United States of America             |

|                  |                            |
|------------------|----------------------------|
| VOCs             | Volatile organic compounds |
| WHO              | World Health Organization  |
| Al               | Aluminum                   |
| As               | Arsenic                    |
| BPA              | Bisphenol A                |
| Cd               | Cadmium                    |
| CH <sub>4</sub>  | Methane                    |
| Cl               | Chlorine                   |
| CO               | Carbon monoxide            |
| Co               | Cobalt                     |
| Cr               | Chromium                   |
| Cu               | Copper                     |
| Fe               | Iron                       |
| H <sub>2</sub> S | Hydrogen sulfide           |
| Hg               | Mercury                    |
| Mn               | Manganese                  |
| NH <sub>3</sub>  | Ammonia                    |
| NH <sub>4</sub>  | Ammonium                   |
| Ni               | Nickel                     |
| NO <sub>x</sub>  | Nitrogen oxides            |
| Pb               | Lead                       |
| SigA             | Secretory immunoglobulin A |
| SO <sub>2</sub>  | Sulfur dioxide             |
| SOAI             | Secondary organic aerosols |
| Zn               | Zinc                       |

## Introduction

Environmental pollution has inherently been associated with health issues including the spread of diseases, i.e., typhoid and cholera, some of which are largely seen as waterborne diseases (Zhao et al. 2015). There are also non-communicable diseases (NCDs) that are brought about due to environmental pollution, such as cancer and asthma, or several defects evident at birth among infants (Reinhart and Townsend 2018). The significant adverse effects of environmental pollution on health-related outcomes have largely been evidenced in low-income countries, where an estimated 90% of the deaths are, in fact, caused by that type of pollution. The two most established forms of pollution in low-income countries are those of air and water. This is contrary to the economies that are rapidly developing, where the toxicity of chemicals and pesticides constitutes the main forms of environmental pollution (Xu et al. 2018).

Several human activities that include, among others, technological applications to change the ecosystems may, also, result in environmental pollution (Nadal et al. 2016). Other forms of pollution may be energy oriented, e.g., light, heat, sound, or several other chemical substances of concern (SoC). The pollutants can either be foreign energies/substances or contaminants that occur naturally (Gworek et al. 2016).

The urbanization and industrialization growth around the world has resulted into introduction of several SoC into the air, hence bringing about the respective type of pollution. It is through the earth's atmosphere that life on our planet is fully supported (Duan et al. 2015).

Yang et al. (2018) identified five classes of pollutants: particulates, sulfur oxides, nitrogen oxides (NO<sub>x</sub>), hydrocarbons, and carbon monoxide (CO). In their study, they reported that in cities and centers, like Karachi and Islamabad, the leading air pollutants included carbon emissions and lead (Pb) (Yang et al. 2018). On the other hand, several types of water pollution exist, resulting in waterborne diseases (Joshi et al. 2016). Some of these waterborne diseases include typhoid, amoebiasis, and ascariasis. Various elements, depending on the concentration they occur, are considered toxic to humans. Therefore, if such an element is released in the air, water, or land, it can result into health complications/issues.

The different types of pollutants can be classified into inorganic, organic, or biological. Organic pollutants include the domestic, agricultural, and industrial waste that adversely harm the life and health of animals and human beings living on the earth. Inorganic pollutants mostly include the potentially toxic elements (PTEs), like mercury (Hg), lead (Pb), and cadmium (Cd). Most of these SoC get accumulated within supply chains, thereby largely harming the earth living organisms (Majolagbe et al. 2017). There are, also, biological pollutants that are anthropogenic derived. The key types of biological pollutants within the environment include viruses, bacteria, and/or several forms of pathogens (Marfe and Di Stefano 2016).

PTEs are regarded as one of the most important environmental pollutants, mainly due to their non-degradability, high persistence, and toxicity (Hahladakis et al. 2013, 2016). In their simplest form, PTEs occur naturally, and they have high atomic weight and density as compared to the one that water has. Of all the pollutants, greater attention has been given to PTEs (Mazza et al. 2015). Usually, these PTEs are present in trace levels in the naturally produced water, but the key challenge is that some of these PTEs are equally toxic even at low concentration levels. Some of these metals like zinc (Zn), cobalt (Co), Hg, Cd, and Pb and the metalloid arsenic (As) have high toxicity even when present in traces. When the body metabolizes these PTEs, they become toxic, being accumulated on soft tissues. There are various avenues through which these PTEs can gain access to human bodies, for instance, through absorption via the skin, food, and air, as well as water (Damigos et al. 2016).

There are various adverse environmental effects related with the PTEs. The majority of the PTEs are non-biodegradable and thus cannot go through degradation either chemically or microbially. Hence, their long-term influence is released via the ground and through the soil. At

the same time, the PTEs can slowly find their way through drinking water which enters the human body. Reportedly, the contamination of water by PTEs has significant influence on all forms of animals (Annamalai 2015).

Toxic chemicals have emerged as a critical source of pollution all over the world. Their situation as environmental pollutants has largely been demonstrated and underpinned among low-income countries, where poor or inappropriate environmental controls take place. Common examples of toxic chemicals being major pollutants include any exposure to PTEs, e.g., Pb and Hg. Of the entire population across the planet, children are the most affected people when it comes to environmental pollution since any particle getting through their system may potentially results in long-term disabilities, as well as premature deaths (Kumar et al. 2017).

In an effort to prevent the aforementioned forms of environmental pollution, most countries have devised ways of preventing or minimizing any occurring impacts through proper disposal and/or burying of waste. Two ways are the most commonly applied: open dumping and/or landfilling. A dump is considered as an opening on the ground that is used for burying trash (Gavrilescu et al. 2015). On the other hand, a landfill is seen as a structure properly designed and built into or on the top of the ground. It is through a landfill that the necessary isolation of waste from the surrounding occurs. A controlled landfill ensures that waste is buried in an engineered manner, isolated from the ground water, while mostly maintaining the waste in a dry form (Indelicato et al. 2017b).

The rationale for the increased use of landfills is the environmental protection and prevention of pollutants entering the soil and, in turn, the underground water. This is obtained via a two way procedure: (a) application of a clay liner to ensure waste does not leave the landfill (sanitary landfills) and (b) application of synthetic liners, including plastic, to ensure that the landfilled waste is separated from the land (municipal landfill) (Mmerekhi et al. 2016). Although landfilling is structured with the aim of reducing waste, it may affect the three types of media previously identified and usually polluted (land, air, and water). After the waste is disposed in landfills, they are compacted to fill the entire area before being buried (Joshi et al. 2017). The rationale for this is to ensure that it will not come into contact with the environment. It, also, ensures that the waste is kept as dry as possible, limiting its contact with air so that it does not easily rot. It has been estimated that about 55% of the waste generated in the USA in 2008 was landfilled (US EPA 2008). Due to its widespread use, it is important to examine environmental pollution and health issues related with the landfills that have emerged across the world presently (Domingo et al. 2015).

## Methodology

The present study will adopt a desk review methodology. Przydatek and Kanownik (2019) define desk study as the collection of information from available sources, and it is one of the low-cost techniques, compared to field work (Przydatek and Kanownik 2019). During desk review, the study scans the available body of literature, carries out an analysis of the secondary data in place, and establishes a reference list at the end of the information/data collected. This helps in ensuring that the produced document is well organized and presented in a manner that is easily accessible.

Various scientific databases have been searched for this purpose, such as ResearchGate, ScienceDirect, eNature, JSTOR, LiveScience, Google Scholar, and Scopus. Different terms have been used in the search field areas, like “Water landfilling” AND “Health impacts” OR “Uncontrolled filling” AND “environment” “Health impacts” OR “Opened dump sites” AND “Health” OR “Landfills” OR “Pollution” OR “Dumpsite” “Environmental issues” OR “Health issues” OR “Waste management.” The produced results were narrowed down to include the last 10 years of publication from 2010 to 2020 to have an updated and critical review. The selected articles included both research and review articles. Upon this selection, the final results were then scanned for relevance to the review by previewing the abstracts and the titles. The relevant articles were then downloaded and reviewed thoroughly.

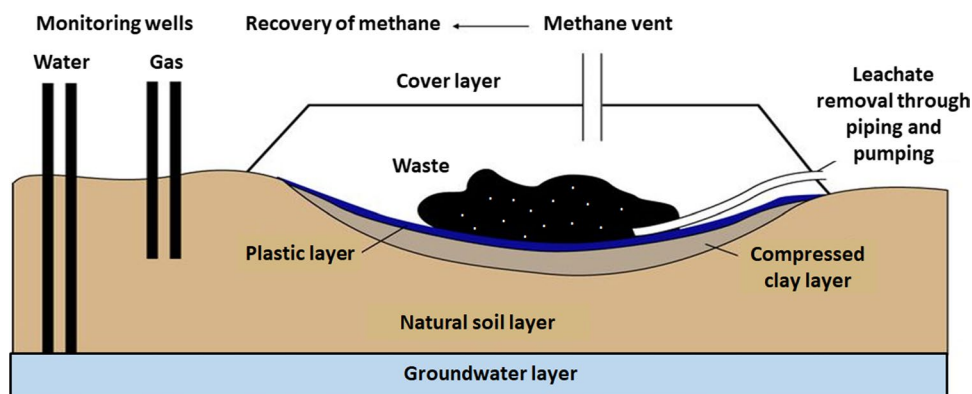
In the present review article, the delivered information will be organized under the following themes and sections: the third section, “Waste landfilling”; the fourth section, “Waste landfilling and environmental pollution”; and the fifth section, “Waste landfilling and human health risks.”

## Waste landfilling

A landfill is an engineered pit, particularly designed for receiving compacted solid waste and equipped with specific covering, so that the waste can be disposed of. There is a lining at the bottom of the landfill so to ensure that the waste does not pollute underground water (see Fig. 1). The design of landfills is such that they accept concentrated wastes in compacted layers so as to lower the volume.

The bottom of a landfill is protected to ensure that underground water is not contaminated. In essence, the deposited waste should be covered by soil at the end of each day. This will ensure that animals and flies are not able to dig up the waste. It also prevents undesired odors to get in the air and pollute the environment. In advanced

**Fig. 1** Typical layout of a waste landfill. (Redrawn from source: available at <http://ocw.jhsph.edu>)



— engineered — landfills, the bottom comprises of liner systems on the sides; there is also a leachate system and an underground monitoring system, as well as a gas extraction system. The gas extracted from landfills is used for energy production. There are, also, landfills possessing anaerobic or aerobic bioreactors: these help in accelerating the process of decomposition of organic waste within the landfill. The overall system provides, also, a conducive environment for microorganisms to decompose the existing waste.

The construction of landfills nearby residential areas is usually associated with effects like the accumulation of  $\text{CH}_4$  gases and contamination of underground water, as well as destruction of properties. This is particularly evident when landfills are not well engineered and/or maintained in a decent operational state; in such cases, there might be some leakages within the underground water, adversely affecting the life of the adjacent residents. In such a situation, people might need to consider relocating. In rural areas, most of the landfills are closed and small in size that rarely affect the quality of living; however, there might influence the value of the nearby properties.

## Types of waste landfills

The most commonly used types of landfills are (a) municipal solid waste landfills, (b) industrial waste landfills, and (c) hazardous waste landfills. There is, also, an emerging landfill type called “green waste landfill” that is, occasionally, being used. All the aforementioned types should, above all, be sanitary. So, before analyzing each independent type separately, it is considered necessary to elaborate and describe the “sanitary” term and present the main characteristics of a sanitary landfill.

### Sanitary landfills

A sanitary landfill is simply a pit whose bottom is protected with a lining so that waste and other forms of trash are

buried in layers, thus making it more solid/stable. It is at the sanitary landfills that waste is isolated from the environment in such a way that it is rendered safe. The waste is only considered to be safe after it has undergone complete biological, chemical, and physical degradation. The degree of waste isolation within the sanitary landfills differs on the basis of the classification of the economies. For instance, in high-income economies, the degree of isolation is deemed to be very high (Ziraba et al. 2016).

The key role in the sanitary landfill is to ensure that all waste is placed in as safe as possible manner. It, also, facilitates safe decomposition of waste with the layers playing an important role in speeding up the process. The  $\text{CH}_4$  gas produced by the decomposition of the landfilled waste is harnessed and used to generate energy. Furthermore, the existing clay layer within the sanitary landfills ensures waste isolation from the environment (Rahmat et al. 2017). In addition, various designs and engineering methods are implemented since this is considered an important step in ensuring that there is no environmental contamination from the solid waste disposed in the sanitary landfills. In the event that the land used for the purpose of landfilling is filled up, impervious clay is used for sealing it and rendering it safe, so that the area can be further used for other activities (Qasim and Chiang 2017).

As earlier indicated, sanitary landfills largely operate by ensuring that waste is layered in large holes. There are various levels of layering that facilitate the entire process of waste decomposition, besides trapping the released toxic gases. The structure of these layers is such that the bottom part carries the smallest volume of waste, whereas the top part should bear the largest one. This is important to ensure that the surrounding land area does not collapse.

There are four specific layers within the sanitary landfills that play an important role in the entire process of the waste decomposition. The first layer is the one found at the bottom, which acts as the foundation of the sanitary landfill. This layer is made of dense and compact clay so that there is no waste seepage and thus no environmental (underground)

pollution. It is on the basis of this reason that the clay used within the sanitary landfills is regarded as impervious (Rajaeifar et al. 2015).

The second layer is the drainage system. This layer protects the landfill from any decomposing that any waste oriented liquids could cause. Since this liquid is regarded as highly toxic, any seepage past the liner layer should be prevented. The role of the drainage system is to drain away the toxic liquids so that it does not get close to the liner system. At the same time, rainfall as well as snow may also create liquids that need to be drained out by this layer. Most of these liquids may contain contaminants that could result into corrosion of the liner system and/or contaminate the soil. In order to reduce these risks, the upper part of the landfills has perforated pipes on the greater part of the liner system. These pipes help to collect the liquids that may access the bottom of the landfills via leaching, hence the name leachates. This leachate is then directed to treatment plants via a plumbing system where it is treated for being reused (Adamcová et al. 2017).

The gas collection system constitutes the third layer of the sanitary landfills. Just as the way the liquids are produced within the landfills, gases are, also, naturally produced. One of these gases is  $\text{CH}_4$ .  $\text{CH}_4$  is toxic, as well as volatile; thereby, its release to the atmosphere could significantly contribute to the global warming effect. To prevent this from happening, extraction pipes are used to ensure the  $\text{CH}_4$  gas is trapped and then transported to the plants for treatment and/or for generation of electricity.

Finally, the fourth layer is used to store the waste. This is the top and largest layer, used to store the waste collected by various companies. To minimize the space needed, the waste is compacted on a daily basis. At the end of this compaction process, a layer of compacted soil is applied on the surface of the sanitary landfill, so as to reduce any odors and the growth of microorganisms that are harmful, e.g., flies and pests.

Generally, sanitary landfills are designed to extend as deep as hundreds of feet, and it can take up to several years before being fully filled, after the compaction process. In the event that they are filled up, a capping is applied. In that case, a clay or plastic layer that is synthetic is introduced in the same manner as at the bottom. This is done to ensure that  $\text{CH}_4$  gas does not escape to the atmosphere and to prevent undesirable odors. At the same time, the top layers are firmly reinforced with an approximately 2–3 feet soil layer, and then plants are planted. In turn, this land may be reclaimed and used for other reasons.

However, despite all these safety processes and measures, there is a large possibility of underground contamination due to the high toxicity of the water oriented from the buried waste. The potential pathways of these toxic wastes may include the water, as well as cultivated soil for the

production of edible plants. To minimize the risk, any filled or repurposed for gardening sanitary landfills are regularly monitored for decades. Their soil is, also, regularly tested to identify any irregularities. In the event any plants are dying, it could be an indication of  $\text{CH}_4$  release from the land. Only when the land has been tested and proven to be safe it can be used for other purposes. However, any heavy-duty activities, i.e., construction works, are not permitted in any case.

### Municipal waste landfills

Municipal waste (also known as trash or garbage) is composed of all solid or semi-solid state waste and mostly includes domestic or household waste. The municipal landfills are one of the preferred methods for dealing with the largely increasing solid waste challenge. Municipal waste landfills are specifically designed so as to receive the household waste and other non-hazardous waste (Krčmar et al. 2018). As of 2009, there are approximately 1,908 municipal landfills in the USA, and these are managed by the states within the area of establishment (US EPA 2009).

### Industrial waste landfills

An industrial waste landfill is where industrial waste is disposed of. While any type of solid industrial waste can be brought to these landfills, they are most often used for construction and demolition (C&D) waste disposal, which is why they are commonly known as C&D landfills. Waste could include concrete, gypsum, asphalt, bricks, and other building components (US EPA 2011).

### Hazardous waste landfills

For obvious reasons, these types of landfills are the most closely regulated and structured landfills. They are specifically designed to hold hazardous wastes in a way that virtually eliminates the chance of it being leached and/or released into the environment. Some of the design requirements for hazardous waste landfills include double liners, double leachate collection and removal systems, leak detection systems, dispersal controls, construction quality assurance, etc. In addition to these design specifications, hazardous waste landfills undergo inspection multiple times a year to ensure that the facility is according to the latest high standards (Hazardous Waste Experts 2019; US EPA 2022).

### Green waste landfills

While these landfills are not officially sanctioned landfills by the EPA, many municipalities are starting to adopt them for placing organic materials so as to get naturally decomposed. These composting sites are on the rise because most

standard landfills and transfer stations are not accepting organic waste like fruits and vegetables.

Common types of green waste will include mulch, weeds, leaves, tree branches, flowers, biodegradable food waste, grass trimmings, etc.

The EPA has estimated that green waste landfills are making a bit of a difference with more than 24,000 tons of yard trimmings sent to these landfills in 2017 (US EPA 2017). The purpose of green waste landfills is to save space in other MSW landfills by keeping a material out that is meant to naturally decompose on its own.

## Theoretical underpinning

Various theories have been developed to explain the waste management and environmental conservation achieved through the establishment of landfills. These theories include the theory of environmentally responsible behavior (ERB), the reasoned/responsible action theory, the theory of planned behavior, the environmental citizenship, the model of human interaction with the environment and the value–belief–norm theory of environmentalism. The ERB theory was originally formulated by Hines, Hungerford, and Tomera in 1986 (Hines et al. 1986). The theory argues that having an intention to act is a key factor that influences responsible behavior for taking care of the environment. Moreover, it debates that the intention of acting, the

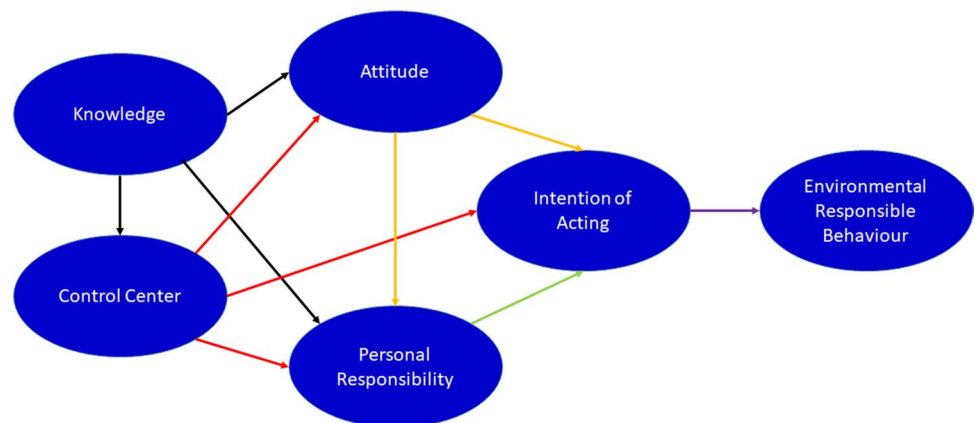
locus of control, the attitudes, the sense of responsibility at the personal level, and knowledge are key tenets influencing the overall ERB (Akintunde 2017; Hines et al. 1986).

The various interactions between the tenets of ERB are summarized in Fig. 2. According to this theory, the internal control center has an influence on the intention of people to act.

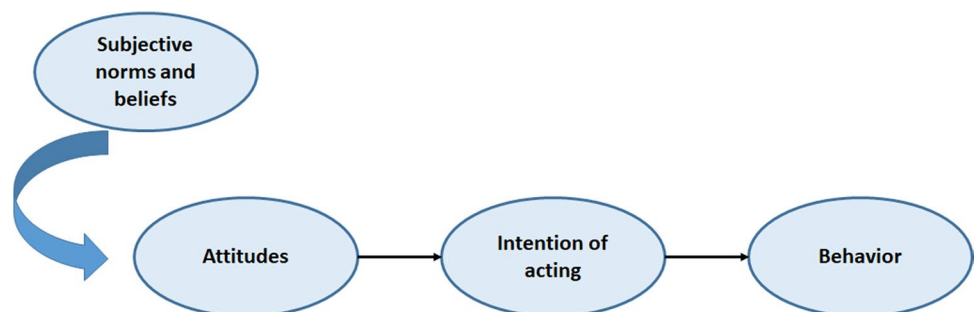
In the management of waste, no single factor exists that brings about a change in current behavior. For instance, despite the existence of stiff regulations forbidding people from dumping waste materials, some people still dump waste or other materials in large cities. As indicated in Fig. 2, knowledge on its own is not adequate enough to lead to responsible actions and behaviors towards the environment.

The reasoned/responsible action theory was initially introduced by Martin Fishbein in 1967 and advanced and extended by Fishbein and Icek Ajzen (Akintunde 2017; Fishbein 1967). The theory argues that the various human behaviors are influenced and shaped by rational thoughts. According to this theory, there is a link between intentions to act and the final behavior of an individual as predicted by the attitudes. They are the subjective beliefs and norms that shape these attitudes. The theory of reasoned action is used to account for the time when individuals are guided by good intentions, but ensuring that these intentions are translated in good actions is affected by inadequate confidence Fig. 3.

**Fig. 2** Schematic representation of the “Theory of Environmentally Responsible Behavior” (ERB). (Redrawn from source: Akintunde (2017))



**Fig. 3** Theory of reasoned/responsible action. (Redrawn from source: Akintunde (2017))



## Waste landfilling and environmental pollution

Landfills have been regarded as the leading avenues that contribute towards emission of greenhouse gases (GHG) across the globe. This is because a large portion of gases, including carbon dioxide ( $\text{CO}_2$ ) and carbon IV oxide are released by the landfills to the air. It is the degradation process that results into all these gases polluting the environment (Papargyropoulou et al. 2015). In addition, the operations carried out at the landfills have been associated with contamination of the underground water sources through the produced landfill leachate. This occurs, particularly, when the liners within the landfills are not as adequate as required. There are, also, odors coming from the landfills that pollute the air, especially of those living in nearby areas. Other pollutants associated with landfills include dust, litter, and rodents (Ilankoon et al. 2018).

According to Hossain et al. (2014), landfill pollution is traditionally classified in several aspects. Maybe the most common categories are those that deal with the receiving air (emissions), water (effluents), and soil (dumps and disposals). A slightly more advanced breakdown would differentiate between inland and marine waters, surface and groundwater, and troposphere and stratosphere, and perhaps, considering the satellites and other types of debris, we should probably add outer space, as well. Most of the debate and regulation of pollution is based around these classifications, but focus is increasingly moving to inter-media impacts, such as the acidification of lakes and streams induced by air pollution or the disposal of sludge and other residuals from air and water pollution control measures on soil or in the ocean.

There are several factors that shape and determine the emission of landfill by-products: the quantity, as well as quality of deposited waste, the number of years a landfill has been operating for, and the climatic factors that surround it. There are some complicated microbiological and chemical reactions occurring within landfills that create gases to the air and hence air pollution. Some of the gases being released from landfills include sulfur dioxide ( $\text{SO}_2$ ) and as well as nitrogen dioxide ( $\text{NO}_2$ ), and these gases have an adverse effect on the environment. Inhaling any of these gases could result into throat and nose irritations that could potentially create asthma. Some of the landfill gases expose people that live around the area of such establishments with respiratory infections (Cucchiella et al. 2017).

The rainfall on landfill sites results in dissolution of inorganic and organic elements of the landfilled waste. In turn, this releases toxic chemicals that leak to the underground water systems. Such type of water shall have high metal content, and it will be toxic if consumed by humans.

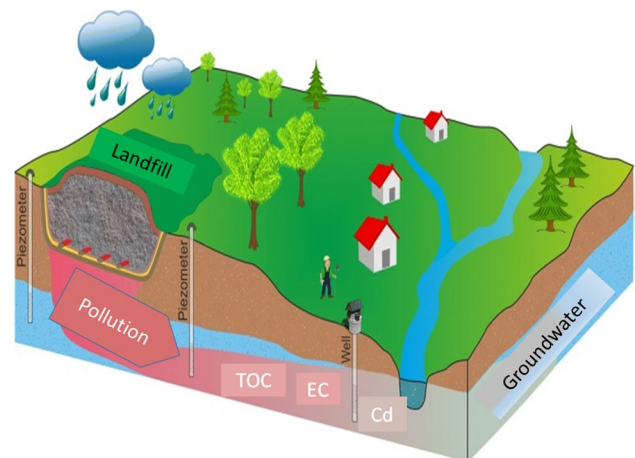
In the event that these chemicals get towards the lake or river systems may pose adverse influence on aquatic life (Zhang et al. 2016). Waste landfills have, also, been associated with air pollution across the world. For instance, it is projected that about two-third of the landfills are made of organic materials that are biodegradable. The decomposition of these materials results into release of  $\text{CH}_4$  gas (Babayemi et al. 2016). This  $\text{CH}_4$  gas helps in trapping heat in the atmosphere since it is regarded as a GHG. The effect of waste landfilling on underground water pollution is illustrated in Fig. 4.

The development of waste landfilling affects, also, the biodiversity. For instance, developing the landfills implies that some 30–300 animal species are lost in every hectare. At the same time, there are some changes among the local species, where some of the birds and mammals are replaced with species feeding of refuse like crows and rats.

Njoku et al. (2019) performed a study in South Africa attempting to establish the link between landfills and environmental pollution. The formulated hypothesis was that the decomposed materials on landfills impact the environment of the surrounding area. It was shown from the results that about 78% of the people who live around these landfills are affected by air pollution. The people living close to landfills report, also, higher health issues including irritation of their eyes and flu. In this study, it was recommended to proper cover the landfill at the end of each day and place agents to dilute the odors (Njoku et al. 2019).

Vavrková et al. (2018) examined, also, landfills and their influence on the environment. In this study, it was shown that the investigated landfill had no direct and/or significant influence on the quality of water (Vavrková et al. 2018).

Danthurebandara et al. (2013) investigated the environmental impact of landfills and concluded that landfills do, actually, play a key role (Danthurebandara et al. 2013).



**Fig. 4** Route of underground water pollution-oriented landfills due to leaching. (Redrawn from source: SPREP (2010))

However, it is from these landfills that approximately 20% of the global  $\text{CH}_4$  quantity is obtained. Besides  $\text{CH}_4$ , there are gases released from these landfills that have high level of toxicity. It is possible that leachate can find its way through the underground water mainly via the flaws found on the liners. Constructing landfills may have an adverse influence in the life of fauna and flora.

Paul et al. (2019) reported in his study that municipal solid waste (MSW) treatment in Bangladesh had a large impact on the environment. More specifically, they reported that MSW leachate caused water pollution affecting, in turn, aquatic species. They, also, reported that open dumping caused soil pollution in Islamabad, affecting soil quality and thereby crop growth, production, and agriculture. Open dumping of solid waste in Nepal led to the spread of infectious diseases. They also reported that as landfills age, the process of mineralization of waste occurs which increases the leaching properties of the waste in the landfill (Paul et al. 2019).

Aljaradin and Persson (2012) studied the influence of landfills on the environment in Jordan. It was shown that the most widely used method for waste management is landfilling (Aljaradin and Persson 2012). However, it was reported that most of the landfills are associated with higher levels of pollution, with periodic leachate and the gas release to the underground water, creating an alarming environmental situation.

Mouhoun-Chouaki et al. (2019) conducted a study on landfills and their influence on the environment. Their specific focus was on establishing the influence of disposal of solid waste on the quality of soil within Nigerian landfills (Mouhoun-Chouaki et al. 2019).

Conte et al. (2018) examined the influence of landfills on air pollution with reference to Italy. It was found that landfills result to air, land, and water pollution to a large degree (Conte et al. 2018).

Adamcová et al. (2017) conducted a study on the environmental assessment of the effects of a municipal landfill on the content and distribution of PTEs in *Tanacetum vulgare*. Much attention was drawn to the effect of landfills on water sources, underpinning the need of taking mitigating actions since most of the population in the area depends on the water on a daily basis. It was, furthermore, reported that in terms of environmental contamination, social inclusion, and economic sustainability, landfill mismanagement is a worldwide problem that needs integrated assessment and holistic approaches/methods for its solution. Attention should be paid in developing and developed countries, where unsustainable solid waste management is prevalent. Differences should be identified between the development of large towns and rural regions where management problems differ, particularly with regard to the quantity of

waste produced and the equipment available for landfill management (Adamcová et al. 2017).

Wijesekara et al. (2014) investigated the fate and transport of pollutants through a MSW landfill leachate in Sri Lanka. Due to the fast pace of natural resource exploitation, technological growth, and industrial expansion, the most striking reason for the landfill and thus worldwide environmental crisis is the deteriorating relationship between man and environment. The pace of change in the environment and its resulting degradation induced by human operations has been so rapid and common. Man's effect on the environment through his financial operations is diverse and extremely complicated, as the natural situation and process transformation or alteration leads to a sequence of modifications in the biotic and abiotic components of the environment. Landfill mismanagement causes severe toxic metal pollution in water, soil, and crops, whereas open burning causes atmospheric pollutant emissions like  $\text{CO}_2$ . Toxic metal-oriented environmental pollution is considered one of the most harmful types of contamination, particularly to human health. Finally, the authors of that study concluded that mismanagement of landfill is a serious danger to the environment as it inhibits sustainable development growth (Wijesekara et al. 2014).

Huda et al. (2017) investigated the treatment of raw landfill leachate via electrocoagulation and with the use of iron-based electrodes; all the parameters involved in the process were studied and optimized. Man's environmental effects can either be direct and intentional or indirect and unintentional. Direct or deliberate effects of human activity are pre-planned and premeditated because man is conscious of the effects, both positive and negative, of any program initiated to alter or modify the natural environment for the economic development of the region involved. Within a brief period of time, the impacts of anthropogenic modifications in the setting are noticeable and reversible. On the other side, the indirect environmental effects of human operations are not premeditated and pre-planned, and these effects arise from those human operations aimed at accelerating the pace of economic growth, particularly industrial development. After a long time, when they become cumulative, the indirect effects are encountered (Huda et al. 2017). These indirect impacts of human economic activity can alter the general natural environment structure, and the chain impacts sometimes degrade the environment to such a degree that it becomes suicidal to humans.

Kalčíková et al. (2015) investigated the application of multiple toxicity tests in monitoring the landfill leachate treatment efficiency. Landfilling is still the prevalent option globally. It has been the main disposal technique of MSW in the latest decades as it is the easiest and most economical practice in many nations, especially in developing ones. Unfortunately, by hosting various stray animals and proliferating insect vectors of a lot of illnesses, these open landfills

lead to severe health hazards. By producing both leachate and biogas, they also pose nuisance and significant environmental effects. The leachate conveys a significant pollution load that mainly consists of toxic metals, organic matter, and a significant community of pathogenic organisms: it causes organic, bacteriological, and toxic metal pollution of soil, surface water, and groundwater by leaching and ground infiltration.

Talalaj and Biedka (2016) conducted a study on the quality assessment of groundwater near landfill sites using the landfill water pollution index (LWPI). Due to the increase in human population and industrial and technological revolutions, waste management has become increasingly challenging and complicated, while processes that regulate the destiny of waste in the soil are complicated and some even poorly known. Sanitary landfill is the most popular and convenient technique of MSW disposal. Sanitary landfills provide better odor-free esthetic control. Often, however, unknown content industrial waste is mixed with domestic waste. Infiltration of groundwater and water supply contamination are prevalent. Unless properly managed, leaching and migration of SoC from waste sites or landfills and the release of various pollutants from sediments (under certain circumstances) pose a high threat to groundwater resources. Protection of groundwater has become a major environmental problem that needs to be addressed. Open dumps are the oldest and most popular way to dispose solid waste, and while thousands have been closed in the latest years, many are still being used (ISWA 2016). Some of the MSW disposal techniques that are frequently used include composting, sanitary landfilling, pyrolysis, recycling, and reuse (Talalaj and Biedka 2016).

Jayawardhana et al. (2016) investigated on MSW biochar for preventing pollution from landfill leachate. The immediate input of (primarily human) waste materials into the environment is usually connected with conventional or classic pollutants. Rapid urbanization and fast population growth have resulted in sewage issues as treatment facilities have failed to keep pace with the need. Untreated sewage from municipal wastewater systems and septic tanks in untreated fields contribute important amounts of nutrients, suspended solids, dissolved solids, petroleum, metals/metalloids (As, Hg, Cr, Pb, Fe, and Mn), and biodegradable organic carbon to the water ecosystem. Conventional pollutants can cause a multitude of issues with regard to water pollution. Excess suspended solids block the sun's energy and thus influence the process of transformation of carbon dioxide–oxygen, which is essential for maintaining the biological food chain. In addition, elevated levels of suspended solids silt up waterways and channels of navigation, necessitating frequent dredging. For drinking and crop irrigation, excess dissolved solids render the water undesirable (Jayawardhana et al. 2016).

Another study conducted on an unlined MSW landfill in the Varanasi district of Uttar Pradesh in India showed that rainfall can have a major impact on the migration of leachate such as Fe, nitrate ( $\text{NO}_3^-$ ), total dissolved solids (TDS), phosphate ( $\text{PO}_4^-$ ), and ions responsible for the electrical conductivity. Post monsoon, the groundwater quality, at several sampled stations, dropped either below the acceptable limit or the extent of groundwater pollution increased (Mishra et al. 2019).

The impact of landfill on the surrounding environment can be diverse depending on the different processes or methods that have been employed to it. In the work conducted by Yadav and Samadder (2018), different scenarios of MSW landfilling were studied, such as collection and transportation ( $S_1$ ); recycling, open burning, open dumping, and unsanitary landfilling without energy recovery ( $S_2$ ); composting and landfilling ( $S_3$ ); recycling, composting and landfilling ( $S_3$ ); and recycling, composting, and landfilling of inert waste without energy recovery ( $S_4$ ). It was found that each of the scenarios showed different degrees of environmental impact. For example,  $S_1$  had the highest contribution to ecotoxicity in the marine ecosystem;  $S_2$  contributed largely to global warming, acidification, eutrophication, and human toxicity;  $S_3$  had high impact on the depletion of abiotic resources such as fossil fuels and also responsible for aquatic and terrestrial ecotoxicity among others (Yadav and Samadder 2018). This demonstrates how a variety of processes can interplay in the landfill system to create a number of impacts, even with human interventions.

Although improper waste disposal results in the emissions of unwanted environmental pollutants such as GHG, a study conducted by Araújo et al. (2018) confirmed that simple sanitary landfills generated the highest amount of  $\text{CO}_2$ , followed by sanitary landfill with  $\text{CH}_4$  collection, municipal incineration, and finally reutilization of woody waste (Araújo et al. 2018). This sheds some hope that proper intervention, such as reutilization and controlled release of pollutants, can be a potential method to reduce the emissions from landfilling.

Kazour et al. (2019) focused on the sources of microplastic pollution in the marine ecosystem. The study concluded that landfills close to the coastal waters were important sources of microplastic pollution in the ocean. Microplastics (MPs) were found in the leachate of active and closed landfills, suggesting that the location of the landfill also plays significant role in its characteristics of releasing plastics. The study found that inner lagoons with low water movement accumulated large amounts of MPs than the outer lagoon, which suggests that these MPs will be available as a contaminant in the marine environment (Kazour et al. 2019).

Another study conducted by He et al. (2019) reported that landfills that accumulate plastics do not act as final sinks for plastics but rather as a new source of MPs. They

suggested that these MPs undergo breakdown due to exposure to the UV light and the prevalent conditions in the landfill (He et al. 2019). This study underpinned the impact of the landfill on coastal environments which are considered fragile ecosystems harboring large diversities.

Meanwhile, a study conducted by Brand and Spencer (2019) investigated the ecological impact of historical landfills located in the coastal zones. They reported that changing climate and proximity to coast can increase the changes of waste release into the waters due to erosion, storms, or even the collapse of the landfill due to age and infiltration of water. Historic landfills are unregulated as they predate modern environmental regulations and are no longer maintained or managed by previous operators. Thus, unmanaged landfills have detrimental impact especially because such landfills can have a wide mixture of waste. The authors of this study speculated that any metal release (derived from the wastes) to the adjacent Thames estuary, should they erode completely, will, i.e., increase the copper (Cu) levels 6.4 times. This will have long-term ecological impacts on the flora and fauna in the immediate vicinity and throughout the marine ecosystem. As of now, most metals exceed interim sediment quality guidelines (ISQG) levels (Brand and Spencer 2019). This study highlights the importance of maintaining the landfills of today's society and their maintenance. Future considerations must also be made to existing landfills so that they may be managed well into the future without threatening the societal ecological balance.

Adamcová et al. (2017) pointed in two ominous directions: (a) towards big and increasing release of certain chemicals, primarily from burning fossil fuels, which are now considerably modifying natural systems on a worldwide scale, and (b) towards constant rises in the use and release of countless biocide goods and poisonous substances into the atmosphere. These raise a more severe issue presenting tremendous problems to the societies, both developed and developing. They concluded that several large-scale social and technological transitions are required to tackle the severe pollution problems in the coming decades (Adamcová et al. 2017).

Guerrero-Rodriguez et al. (2014) suggested that today's pollution from landfill is integrally linked to financial manufacturing, contemporary technology, lifestyles, sizes of populations of humans and animals, and a host of other variables. Except for wide macro-transitions with various social benefits, it is unlikely to yield. These transitions include moving away from fossil fuels and waste-intensive techniques, bringing to bear our most advanced science, changing prices and other financial incentives, perceiving emissions as either trans boundary or global, and moving towards world population that is very stable (Guerrero-Rodriguez et al. 2014).

According to Majolagbe et al. (2017), land is frequently used as a waste treatment recipient, accepting spills of waste. Land pollution is the degradation of the earth's land surface by bad farming methods, mineral exploitation, industrial waste dumping, and indiscriminate urban waste disposal. For a lot of municipal and some industrial waste, recycling of materials is practical to some extent, where a tiny, but increasing percentage of solid waste, is being recycled. However, when waste is mixed, recovery becomes hard and costly.

The former statement has been analyzed, along with new proposed methods in order to sort ferrous and nonferrous metals, plastics, paper, glass, etc., and many communities are implementing recycling programs that require separation of commingled waste. Developing better handling techniques, inventing new products for recycled materials, and finding new markets for them still remain crucial problems for the recycling sector (Hahladakis and Aljabri 2019; Hahladakis and Iacovidou 2018, 2019; Hahladakis et al. 2018; Majolagbe et al. 2017).

## Waste landfilling and human health risks

Love Canal is one of the most widely acknowledged landfill which is located in New York. During the periods of the 1930s to the 1940s, a huge volume of toxic materials was deposited. This was followed by establishing residential houses and learning institutions around this landfill in the 1950s. As of the mid-1970s, a number of chemicals were detected to have been leaked to the nearby streams and sewers. This has resulted into various studies being carried out to explore how this affected the human health. Most of the studies carried out have revealed that landfilling has, indeed, been associated with health issues, as a result of emissions of SoC to the air.

In Italy, studies have been carried out to reveal any effects associated with living closer to areas where there is landfilling. It was revealed that hydrogen sulfide ( $H_2S$ ) was associated with lung cancer and other respiratory health issues. The most affected part of the population was the children.

Vrijheid (2000) reported on the health issues that are related with people living closer to landfilling. The trigger point for this study was the fact that some specific form of cancer and defects at birth as well as low birth weight have been linked with individuals that live closer to landfilling areas. It was shown that living closer to landfilling areas is associated with respiratory diseases like asthma. This is largely attributed to the emissions of the gases to the air that affect the health outcomes of individuals (Vrijheid 2000).

Limoli et al. (2019) reported that illegal landfilling has adverse health effects on people living near the landfills and that it is more harmful to children, as their immune

systems are still developing and because they spend most of the time outside their homes. They noted that health impacts can range from acute intoxication to carcinogenicity, endocrine-related toxicity, genotoxicity, and mutagenicity, depending on the contaminants. Upon contact with water, some contaminants dissolve and leach into the soil and contaminate the underwater table. Such pollutants that dissolve into the liquid phase include ammonium nitrogen that can cause eutrophication, chlorides that can alter the reproductive rates of marine animals and plants, organic matter that contributes to the deterioration of the water quality, persistent organic pollutants (POPs) that can cause bioaccumulation, and biomagnification in the food chain and sulfates that may increase nutrient levels in the water body, leading to eutrophication, in addition to fostering the production of methylmercury by some bacteria which is toxic. As part of the gaseous emissions, NO<sub>x</sub> triggers photochemical smog and contributes to acid rain and phytotoxic, particulate organic matter reduces photosynthetic rate and aids in photochemical smog formation, sulfur oxides cause acid rains, and volatile organic compounds (VOCs) cause the formation of harmful ground-level ozone. Besides these, many types of hazardous wastes can also be added such as PTEs that lower water quality; radionuclides and pathogenic waste are severely harmful for the living organisms (Limoli et al. 2019).

Mattiello et al. (2013) sought to determine how disposing solid waste in landfills affects health outcomes. The study systematically reviewed the available information on the subject under consideration. It was shown that the health issues linked with landfills include respiratory diseases and possible hospitalization especially among children (Mattiello et al. 2013). Maheshwari et al. (2015) focused on landfill waste and its influence on health outcomes. The review of information showed that landfills are associated with air, water, and land pollution problems around the world. These forms of pollution have adverse influence on people especially children who have weak immunity systems. Pollution of the environment through dumping of waste is associated with health issues on a long-term basis. The gases that are emitted from the landfills result into environmental pollution, and they are also associated with a number of issues related with cancer (Maheshwari et al. 2015).

Xu et al. (2018) conducted a study to find out the correlation of air pollutants associated with land filling on the respiratory health of children living in the proximity of a particular landfill in China. They reported that CH<sub>4</sub>, H<sub>2</sub>S, CO<sub>2</sub>, NH<sub>4</sub>, and other air pollutants were released with anaerobic decomposition of waste in the MSW landfills. While the concentration of these pollutants have been published to be lower than regulatory limits, any exposure to land fill gases (LFG) such as those of H<sub>2</sub>S and NH<sub>4</sub>, even at lower concentrations, had a negative impact on the respiratory

system and the general immunity of children living near the landfill. Children living closer to the landfills showed lower levels of lysozyme associated with exposure to CH<sub>4</sub> and H<sub>2</sub>S and lower SIgA levels associated with H<sub>2</sub>S and NH<sub>3</sub>. These two factors are measured as they are among the first line of defense in the human body, and their lower levels in children reduced their immunity. They, also, established that as the distance from landfill increases, the effects are reduced (Xu et al. 2018). This experiment yet again establishes the health impact landfills have on young children as a manifestation of a pathology and as an impact on their immune system and its development.

Triassi et al. (2015) conducted a study on the environmental pollution from illegal waste disposal and health effects. Improper landfill management and shipments of illegal waste can have adverse environmental and public health effects. Different handling and disposal operations may result in negative effects arising in land, water, and air pollution. Insufficiently disposed or untreated waste can trigger severe health issues for communities surrounding the disposal zone. Waste leakages can contaminate soils and streams of water and cause air pollution by, i.e., emissions of PTEs and POPs, thereby creating eventually health risks. Other nuisances created by uncontrolled or mismanaged landfills that can negatively impact individuals include local-level effects such as deterioration of the landscape, local water, air pollution, and littering. Therefore, proper and environmentally sound management of landfill is essential for health purposes (Triassi et al. 2015).

A study conducted in Serbia revealed similar findings of high concentration of PTEs, such as Cu and Pb in groundwater and Hg in soil due to the leaching from uncontrolled local MSW landfills. Hg was reported to have high ecological risk for that region (Krčmar et al. 2018).

Melnyk et al. (2014) conducted a study on chemical pollution and toxicity of water samples from stream receiving leachate from a controlled MSW landfill. A relevant factor concerning health effects of landfill management is how much and which population is involved in such risks. Unlike in the case of urban air pollution, exposure to pollution from landfill mismanagement facilities does not affect all the inhabitants of an urban area but only a small proportion of the population residing nearby the landfill. Living in the vicinity of a landfill can pose a health danger to citizens as they may be subjected to pollutants through various routes: inhalation of SoC emitted by the site and contact with water or polluted soil, either directly or through the consumption of products or contaminated water. The greatest issues are illegal, uncontrolled landfills that receive waste at source without any choice (Melnyk et al. 2014).

Palmiotto et al. (2014) conducted a study on the influence of a MSW landfill in the surrounding environment. Landfill has been regarded as the oldest form of waste

treatment and the most prevalent technique of structured waste disposal and has remained so in many parts of the globe. A modern landfill is an engineered establishment, specially built and equipped with protected cells. Despite the reality that growing quantities of waste are being reused, recycled, or energetically valued, landfills still play a significant role in the waste management infrastructure of many countries. The degradation of waste in the landfill results in the production of leachate and gases. These emissions pose potential threats to human health and environmental quality. Landfilling has environmental impacts, primarily because of the long-term manufacturing of CH<sub>4</sub> and leachate (Palmiotto et al. 2014).

A research by Abd El-Salam and Abu-Zuid (2015) on the effect of waste leachate on soil quality in Egypt proposed the need to adjust variables to enhance anaerobic biodegradation leading to leachate stability in relation to ongoing groundwater surveillance and leachate therapy procedures. Landfill construction and management have ecological impacts that can lead to modifications in the landscape, habitat loss, and wildlife displacement. Socio-economic effects of landfills include hazards to public health arising from leachate contamination of the ground or groundwater, the spread of litter into the wider setting, and insufficient recycling operations on site. Nuisances like flies, odors, smoke, and noise are often cited among the reasons why people do not want to live near landfills. However, depending on the real distance from the landfill, landfills are likely to have an adverse impact on housing values (Abd El-Salam and Abu-Zuid 2015).

Furthermore, Rezapour et al. (2018) found that uncontrolled leak of leachate from landfills drastically increased the concentration of various PTEs in the soil which interacted with the crops grown there. They reported that a number of metals were found in moderate quantities, except Cd which was above limits and posed moderate intensity non-carcinogenic risk to the people consuming the wheat. This study however reported that the cancer risk to the local resident was low. This study illustrates the extent of landfilling-generated pollution. The PTEs could interact with the soil system and enter the food chain, thus causing harmful effects to the human population (Rezapour et al. 2018).

Giusti (2009) stated that the ways of exposure that result in health effects associated with waste landfilling are inhalation, consumption, and the food chain. He, also, noted that the health risks associated with individuals directly involved in the waste management system is much higher due to their proximity to the hazard and that the cases of adverse effects are higher among workers than the residents near the landfill. Moreover, he underpinned the fact that the waste management industry has the highest occupational accidents than other professions. For populations living in close proximity to landfills, the risk of birth defects and cancer increased (Giusti 2009).

A study conducted in the island of Mauritius, dealt with the impact of non-hazardous solid waste coming from the only landfill of the island. It was found that vomiting and nausea were consistent symptoms among the population. A large difference in the body mass index of men as compared to their control group was, also, noticed, a pattern that was not observed among women or children, thereby indicating that the effects of pollution can vary on the gender of the individual. Interestingly, it was also found that many other symptoms of health issues were reported; however, they were attributed to either the confounding factors or to a “pan symptom” effect, personal bias. Although this exclusion may be due to the nature of this study being dependent on patient’s information, it provides new dimension to think about personal bias or the placebo effects especially when counteracting seemingly non-threatening diseases associated with landfills, unless proved otherwise by medicinal science (Goorah et al. 2009).

Other studies conducted by various researchers showed that there was an increased risk of malformation of babies among women who lived close to hazardous landfill sites in Washington state and the risk increased among those living in urban areas compared to rural areas (Kuehn et al. 2007).

In the research of Damstra (2002), it was stated that exposure to endocrine-disrupting compounds (EDCs) can put women at risk for breast cancer among other factors, although there are no studies that show a direct increase in the levels of breast cancer with exposure to EDC. However, Damstra claimed that the time of exposure of these chemicals in these women’s lifespan determines the risk. He also reported that studies have shown that exposure to polychlorinated biphenyls (PCBs) in newborn and young children has resulted in neurobehavioral changes, such as immaturity in motor functions, abnormal reflexes, and low psychomotor scores, and these changes may continue into their childhood. He, also, reported that studies suggest that when mothers exposed to low levels of PCBs give birth, the babies have subtle neurobehavioral alterations (Damstra 2002).

Martí (2014) performed a human health risk assessment of a landfill based on volatile organic compounds emission, emission, and soil gas concentration measurements. Direct dumping of untreated waste in rivers, seas, and lakes can cause severe health hazards to accumulate toxic substances in the food chain through the plants and animals that feed on it. Human health may be affected by exposure to hazardous waste, with kids being more susceptible to these pollutants. Indeed, immediate exposure can lead to illnesses through chemical exposure, as chemical waste release into the atmosphere leads to chemical poisoning (Martí 2014).

Agricultural and industrial waste can also pose severe health hazards. Other than this, the co-disposal of municipal, industrial, and hazardous waste can expose individuals to chemical and radioactive risks. Uncollected solid

waste can also obstruct the runoff of storm water, leading to the formation of stagnant water bodies that become the disease's breeding ground. Waste dumped near a source of water also causes water body or groundwater source contamination (Krčmar et al. 2018).

Sharifi et al. (2016) performed a risk assessment on sediment and stream water polluted by toxic metals released by a MSW composting plant. Solid waste disposed of in landfills is generally subjected to complicated biochemical and physical procedures resulting in both leachate and gaseous emissions being produced. When leachate leaves the landfill and reaches water resources, it can lead to pollution of surface water and groundwater. Gas and leachate generation, mainly due to microbial decomposition, climatic circumstances, refuse features, and landfilling activities are unavoidable implications of the practice of solid waste disposal in landfills. In both current and new installations, the migration of gas and leachate away from landfill limits and their release into the atmosphere pose severe environmental concerns. These issues result to fires and explosions, vegetation harm, unpleasant odors, landfill settlement, groundwater pollution, air pollution, and worldwide warming in addition to potential health risks (Sharifi et al. 2016).

Liu et al. (2016) conducted a study on health risk impact analysis of fugitive aromatic compound emissions from the working face of a MSW landfill in China. Over the past three decades, worldwide concern has been growing with regard to the effects of landfill mismanagement on public health. Human exposure to pollution from landfill is thought to be more intense in human life now more than ever. Pollution from landfills can, also, be caused by human activity and natural forces. The significance of environmental factors to the health and well-being of human populations is increasingly apparent. Landfill is a global issue, and it has a huge ability to impact human population health.

Landfill, in the densely settled urban-industrial centers of the more developed countries, reaches its most severe proportions. More than 80% of polluted water was used for irrigation in poor nations around the globe, with only 70–80% of food and living safety in urban and semi-urban-industrial regions (Assou et al. 2014).

Kret et al. (2018) conducted a study on respiratory health survey of a subsurface smoldering landfill. The water we drink is vital to our well-being and a healthy life, but unfortunately polluted water and air are prevalent worldwide. Landfill is tangled with unsustainable anthropogenic activity, leading to significant public health issues. Some of the illnesses connected with landfill pollution are infectious diseases such as cancer, birth defects, and asthma. Environmental health issues are not just a conglomerate of worries about radiological health, treatment of water and wastewater, control of air pollution, disposal of solid waste, and

occupational health, but also a danger to future generation (Kret et al. 2018).

By looking at its definition, pollution is considered to be very harmful, too much of which occurs at the incorrect location. However, some erstwhile pollutants are useful in suitable amounts. Aquatic life requires phosphates and other plant nutrients; however, too much of these nutrients and the outcomes of eutrophication are harmful. CO<sub>2</sub> in the atmosphere helps to maintain the earth warm enough to be habitable, but the accumulation of vast amounts of surplus CO<sub>2</sub>, generated by the use of fossil fuel and other sources, is now threatening to change the climate of the planet. Other pollutants, such as dioxin and PCBs, are so toxic that even the smallest quantities pose health risks, such as cancer and impairment of reproduction. Pollutant releases to the environment are most frequently the casual by-product of some helpful activity, such as electricity generation or cow rearing. This sort of pollution is a form of waste disposal. It happens when the financial expenses of eliminating pollution are greater than the financial advantages, at least the polluter benefits (Zhang et al. 2016).

Although nutrients such as nitrogen and phosphorus are vital to the aquatic habitat, they may trigger over fertilization and accelerate the lakes' natural aging (eutrophication) cycle. In turn, this acceleration generates an overgrowth of aquatic vegetation, huge overall shifts, and a general change in the biological community from low productivity with many varied species to elevated productivity with big numbers of a few less desirable species (Koda et al. 2017). Bacterial action oxidizes organic carbon that is biodegradable and consumes dissolved oxygen in water which may cause a threat to the aquatic life. In extreme cases where the loading of organic carbon is high, oxygen consumption may result in an oxygen depression that is adequate to cause fish killing and severely interrupt the development of related organisms that require oxygen to survive. A result of this pollution is water hyacinth and other floating aquatic vegetation.

It was deemed appropriate and necessary to tabulate the rest of the articles reviewed in an effort to include as much information as possible on the environmental and health effects associated with landfilling. Table 1 summarizes and depicts a consolidated view of these articles reviewed, together with any associated environmental and/or health impact of the various types of landfills reported therein.

## Conclusions

This study aimed at assessing the environmental pollution and health effects associated with waste landfilling. A desk review design was adopted, and information was gathered from the already available sources. The literature review was centered along three themes: waste landfilling, waste

**Table 1** Environmental and health impacts of landfilling

| Article No. | Type of landfill (if provided)      | Environmental impact                                                                                                                                                                                                                 | Health impact                                                                                                                                                                                                                                      | References                  |
|-------------|-------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| 1           | Non-hazardous waste landfills       | -                                                                                                                                                                                                                                    | No suggested excess risk to the residents                                                                                                                                                                                                          | Schlosser et al. (2016)     |
| 2           | Landfill                            | -                                                                                                                                                                                                                                    | Impaired hepatic health in those with occupational or environmental exposure                                                                                                                                                                       | Ogunlaja et al. (2019)      |
| 3           | MSW landfill                        | Leachates polluted the soil and surface water but did not reach the groundwater                                                                                                                                                      | Potential emergence of infectious diseases                                                                                                                                                                                                         | Sánchez-Arias et al. (2019) |
|             |                                     | Dust resuspension during waste separation, compaction, and coverage practices of the landfill caused the release of PM <sub>10</sub> particles causing air pollution                                                                 | Odor caused stress, bad mood, annoyance, and a feeling of helplessness to the people living in the vicinity of the landfill                                                                                                                        |                             |
| 4           | Landfill                            | -                                                                                                                                                                                                                                    | Diseases such as asthma, flu, cough, stomach ache, and skin infections were related to the landfill                                                                                                                                                | Sarigiannis (2017)          |
|             |                                     | -                                                                                                                                                                                                                                    | Exposure to two major waste management facilities (landfill and plastic recycling) studied. Proximity to landfill lowered neurodevelopmental scores in children and was associated to toxic metal exposure; increased risk of cancer later in life |                             |
| 5           | Regulated and unregulated dumpsites | Leachates with high levels of nitrates, phosphates, PTEs, Mn, Cr, Ni, Cd, and organic compounds which exceeded the US EPA standard for drinking water                                                                                | Cellular organelles and DNA damages in in vitro cytotoxicity assays in human derived cells                                                                                                                                                         | Khalil et al. (2018)        |
| 6           | Landfill                            | -                                                                                                                                                                                                                                    | Upregulation of liver activity enzymes coupled with significant damage expression in the liver, spleen, and bone marrow DNA in mice                                                                                                                | Alimba et al. (2016)        |
|             |                                     | -                                                                                                                                                                                                                                    | Molecular damages can cause cancer                                                                                                                                                                                                                 |                             |
| 7           | Landfill                            | BPA contamination was found to be the highest near the BPA manufacturing areas and leached into water bodies                                                                                                                         | The leachates were found to cause DNA damage, cell death, change in morphology, and detachment from the substratum and cytoplasmic vacuolations in the treated cells                                                                               | Huang et al. (2012)         |
| 8           | Uncontrolled municipal landfill     | Leachate containing As, Al, Pb, Cl, NH <sub>4</sub> <sup>+</sup> , Fe, and Mn contaminated underground water, and contamination decreased with increasing distance, and groundwater at a depth of 30 m was not suitable for drinking | BPA was reviewed to cause a number of health issues such as causing diabetes, cardiovascular disease, increased cancer risk, and DNA damage                                                                                                        | Han et al. (2014)           |
| 9           | Landfills                           | -                                                                                                                                                                                                                                    | -                                                                                                                                                                                                                                                  |                             |
|             |                                     | -                                                                                                                                                                                                                                    | Review concluded that the results from landfill studies showed congenital malformations were the most conclusive reports on human health                                                                                                           | Giusti (2009)               |

**Table 1** (continued)

| Article No. | Type of landfill (if provided)   | Environmental impact                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Health impact                                                                                                                                                                                                                                                                                                                                         | References           |
|-------------|----------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|
| 10          | Hazardous waste landfills        | Over a long period of time, leachate rate was much higher than short-term leaching<br>Contaminated drinking water                                                                                                                                                                                                                                                                                                                                                                                                                                    | Some metals like Zn, Mn, and Ni had non-carcinogenic effects<br>While Pb had both carcinogenic and non-carcinogenic effects<br>The toxicity of the substances varied based on concentration and morphology<br>PCDDs and PCDFs levels in air were low and did not have any carcinogenic or non-carcinogenic risks in the area surrounding the landfill | Xu et al. (2018)     |
| 11          | MSW landfill                     | -                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | -                                                                                                                                                                                                                                                                                                                                                     | Li et al. (2017)     |
| 12          | MSW landfill                     | Landfills are the sources of MPs and not a sink for plastics as the MPs were resultants of plastic fragmentation                                                                                                                                                                                                                                                                                                                                                                                                                                     | -                                                                                                                                                                                                                                                                                                                                                     | He et al. (2019)     |
| 13          | MSW landfill                     | VOCs are also responsible for the formation of tropospheric ozone and SOA (secondary organic aerosols) that causes air quality degradation, odor nuisances in the surrounding areas of landfills, and related psychological stress on inhabitants<br>Concentrations of PTEs such as Fe, Mn, Cd, and Pb were above allowed limits<br>Soil concentration of Pb, Fe, and Mn were higher, accumulation of Mn and Zn in plants were observed indication bioaccumulation and water had significant levels of all the metals mentioned except for Fe and Pb | Certain VOCs have potential to cause cancer in high concentrations. Studies on impacts of low concentration of VOCs are not conclusive or abundant                                                                                                                                                                                                    | Nair et al. (2019)   |
| 14          | Open “landfill”                  | -                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | -                                                                                                                                                                                                                                                                                                                                                     | Alam et al. (2019)   |
| 15          | Open dumps or “controlled” dumps | Leachate has polluted drinking water wells and underground tanks in the vicinity of San Gaspar site; high biological contamination in leachate from Los Laureles site which crosses an irrigation source; high Pb levels in El Taray site<br>H <sub>2</sub> S was the major contributor to olfactory pollution                                                                                                                                                                                                                                       | -                                                                                                                                                                                                                                                                                                                                                     | Bernache (2003)      |
| 16          | MSW landfill                     | -                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | The individual carcinogenic and non-carcinogenic effects (sulfur compounds) were lower than permissible limits; however, the combined risk of both was far beyond permissible limits                                                                                                                                                                  | Wu et al. (2018)     |
| 17          | Solid waste landfill             | -                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | There are no significant harmful impacts on the population based on the risk assessment model that indicates that the HI for carcinogenic and non-carcinogenic pollutants in the below thresholds                                                                                                                                                     | Davoli et al. (2010) |

**Table 1** (continued)

| Article No. | Type of landfill (if provided) | Environmental impact                                                                                                                                                                                                   | Health impact                                                                                                                                                                                                                | References                  |
|-------------|--------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| 18          | Waste dumpsite                 | -                                                                                                                                                                                                                      | PBDE poses no to low risk on the population but can cause cancer risks in the future due to their bioaccumulation properties. PCBs showed low-moderate and high potential carcinogenicity depending on the mode of transfer  | Hafeez et al. (2016)        |
| 19          | Open landfill                  | -                                                                                                                                                                                                                      | Health risk assessment showed that pathogenic bio-aerosols deposited in adults, while their finer PM affected children. Complaints included cough, chest pain, asthma, aspergillosis etc.                                    | Madhwal et al. (2019)       |
| 20          | Uncontrolled dumping           | Contamination of water canal with Cd, As, Hg, phthalates, bisphenol A, and PAHs above maximum allowed limits from pyrogenic and petrogenic sources                                                                     | -                                                                                                                                                                                                                            | Borjac et al. (2019)        |
| 21          | Open dumping                   | The geotechnical properties of the soil (maximum dry density, specific gravity, cohesion, CBR, permeability) were significantly deteriorated due to dumping                                                            | -                                                                                                                                                                                                                            | Sharma et al. (2018)        |
| 22          | Open waste dumping             | Alteration of soil properties such as high pH, TDS, and EC. Increase in toxic metal concentration in the soil (Pb, Cu, Ni, Cr, Zn). Plant diversity in the region decreased due to the change in soil characteristics. | -                                                                                                                                                                                                                            | Ali et al. (2014)           |
| 23          | MSW dumpsite                   | Contamination of drinking water with moderately high levels of toxic metal due to percolation of leachate                                                                                                              | -                                                                                                                                                                                                                            | Biswas et al. (2010)        |
| 24          | Open dumpsite                  | -                                                                                                                                                                                                                      | Bio-aerosols containing <i>Aspergillus fumigatus</i> and fungi caused chronic cough, chronic phlegm in waste workers with higher prevalence among smokers than non-smokers. It also varied with the waste activity performed | Akpeimeh et al. (2019)      |
| 25          | Waste dumping                  | Waste entered water systems such as river                                                                                                                                                                              | -                                                                                                                                                                                                                            | Kang et al. (2020)          |
| 26          | Illegal dumping                | -                                                                                                                                                                                                                      | Increased cancer mortality and congenital malformations were found to be in excess in studies                                                                                                                                | Marfe and Di Stefano (2016) |
| 27          | MSW dumping and burning        | Releases CO <sub>2</sub> , CH <sub>4</sub> , SO <sub>2</sub> , NO <sub>x</sub> , CO, NH <sub>3</sub> in tons and are important air pollutants that causes changes in the climate                                       | Reviewed studies show health impacts such as respiratory disease, heart diseases, and allergic hypersensitivity                                                                                                              | Das et al. (2018)           |
| 28          | Lined landfills                | Concentrations of perfluoroalkyl substances were found to be higher in leachate which is of concern as they are persistent                                                                                             | -                                                                                                                                                                                                                            | Harrad et al. (2019)        |

**Table 1** (continued)

| Article No. | Type of landfill (if provided)    | Environmental impact                                                                                                                                                                                                                                           | Health impact                                                                                                                                                                                                                                   | References                             |
|-------------|-----------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------|
| 29          | Landfills                         | -                                                                                                                                                                                                                                                              | Landfills can be a source of dioxin pollution which can cause craniofacial defects. It also has teratogenic effects on exposed populations                                                                                                      | (Leśków et al. 2019)                   |
| 30          | Municipal landfill                | Landfills are capable of causing air pollution including the release of various metals and hazardous compounds that could be detected with the help of lichens and could have been unnoticed in surveys                                                        | -                                                                                                                                                                                                                                               | (Sujetovienė et al. 2019)              |
| 31          | MSW landfill                      | Improper drainage systems of landfills could cause migration of the leachate to the underground water                                                                                                                                                          | -                                                                                                                                                                                                                                               | Przydatek and Kanownik (2019)          |
| 32          | MSW landfill                      | Air pollution                                                                                                                                                                                                                                                  | Landfills act as a source of emission of bacterial cells and their endotoxins which can pose a threat to the health and safety of the workers and those living by. The concentrations of these near the landfills varied on a number of factors | Cyprowski et al. (2019)                |
| 33          | Dumping of wastes and landfilling | Dumping of factory waste consisting of POPs evidently increases its concentration in surrounding air. This is a source of air pollution<br>If washed down, they could cause water pollution                                                                    | -                                                                                                                                                                                                                                               | Navarro et al. (2019)                  |
| 34          | Dumping of waste                  | Wastes dumped in the form of landfills after coal mining and processing poses as significant contributors of Hg. They are present in much higher concentration than background levels leading to the pollution of the soils and the land on which it is dumped | -                                                                                                                                                                                                                                               | Antoszczyszyn and Michalska (2016)     |
| 35          | MSW landfill                      | Groundwater was contaminated with due to leachate<br>This implies that improper lining or absence of results in much groundwater contamination                                                                                                                 | -                                                                                                                                                                                                                                               | Grygorczuk-Petersons and Wiater (2016) |
| 36          | Landfill                          | Landfills release micro-pollutants due to the presence of organic compounds in them and their release continues even after their closure posing a risk even after their lifetime                                                                               | -                                                                                                                                                                                                                                               | Vodyanitskii and Yakovlev (2016)       |

**Table 1** (continued)

| Article No. | Type of landfill (if provided)  | Environmental impact                                                                                                                                                                                                                                                                                                                                                      | Health impact                                                                                                                                                                                                                                                                                         | References                 |
|-------------|---------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------|
| 37          | MSW landfill                    | -                                                                                                                                                                                                                                                                                                                                                                         | Release of aromatic compounds from MSW landfills increases carcinogenic effects almost to 1.5 km downwind in normal case scenarios and extended up to 4 km downwind in worst case scenarios. This continues to be harmful to populations that can live near these type of landfills in poor countries | Liu et al. (2016)          |
| 38          | MSW landfill                    | They contaminated the underground water with hazardous organic pollutants such as PAHs, PCBs, and PCDFs among 82 other contaminant parameters. They also were above legislative limits. This may also shed light to the fact that they are either not maintained or that release of contaminants is hard to control or monitor unless one looks for specific contaminants | -                                                                                                                                                                                                                                                                                                     | Indelicato et al. (2017a)  |
| 39          | Landfill garbage site           | Case study of the impact of the leachate on groundwater quality, which was found to be deteriorated                                                                                                                                                                                                                                                                       | -                                                                                                                                                                                                                                                                                                     | Van Giang and Duan (2017)  |
| 40          | MSW landfill                    | Groundwater quality was found to be deteriorated in 98.85% of the samples collected near the landfills. This yet again shows the extent of water quality impeder landfills are                                                                                                                                                                                            | -                                                                                                                                                                                                                                                                                                     | Najafi Saleh et al. (2019) |
| 41          | Domestic waste landfill         | Landfills release greenhouse and toxic gases due to aerobic and anaerobic processes (respiration) under different environmental conditions. This ultimately contributes to the growing problem of global warming                                                                                                                                                          | -                                                                                                                                                                                                                                                                                                     | Sainova et al. (2019)      |
| 42          | Illegal dumping and landfilling | Illegal dumping of municipal waste has seen to drastically lower groundwater quality in two out of the five landfill sites observed                                                                                                                                                                                                                                       | -                                                                                                                                                                                                                                                                                                     | Naveen and Malik (2019)    |

landfilling and environmental pollution, and waste landfilling and health issues.

From the reviewed information, it was established that landfills play an important role as far as disposal of solid waste is concerned. It was shown that majority of the countries have adopted landfilling as waste management systems. The literature indicates that some landfills have lining at the bottom to prevent leakage of the waste into the underground water. The present review revealed, also, that landfills are meant to create conducive environment that enhances micro-organisms' activities and thus decomposition of the waste.

Despite the role played by landfills in the waste management sector, the reviewed literature showed that they are linked with environmental pollution. Landfills were seen to have an influence on biodiversity and the flora and fauna, as well as the aquatic life. Literature indicates that landfills are associated with environmental pollutants including mice and other rodents. The gases released from landfills result into air pollution of the area surrounding the establishment, in addition to the release of bio-contaminants. Landfills are, also, associated with pollution of the underground water, especially when the lining at the bottom is not sufficient to prevent leakage of the waste and a large body of literature supports this.

This article investigated, also, the health issues associated with landfilling. It was concluded that through landfills, there are possible chances of emission of gases into the air like CO<sub>2</sub>, H<sub>2</sub>S, CH<sub>4</sub>, and NO<sub>x</sub>. These gases have been associated with respiratory health challenges and some specific types of cancer, e.g., lung cancer. Carcinogenic risks were found to vary between studies but were mostly attributed to the varying characteristics of the landfill. A variety of literature suggests, also, that the environmental pollution caused by landfills creates greater risks to children living in the vicinity of the landfills. Teratogenic effects of certain elements found in the contaminated groundwater were, also, observed. Unarguably, humans produce a large amount of waste, and landfills provide the easiest and relatively efficient way of tackling these waste. However, landfilling has larger deleterious effects that seem to outweigh the benefits it provides. Better technological involvement in waste segregation and appropriate waste management techniques, stronger enforcement of regulations surrounding landfills, and setting up a larger concrete minimum distance for settlements are some of the necessary measures to be seriously considered and taken in the near future.

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## Declarations

**Competing interests, ethics approval, consent to participate, and consent for publication** We wish to confirm that there are no known conflicts of interest associated with the publication of the present work and there has been no financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We understand that the corresponding author is the sole contact for the editorial process (including the editorial manager and direct communications with the office). He/she is responsible for communicating with the other authors about progress, submissions of revisions, and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the corresponding author and which has been configured to accept email from: john\_chach@yahoo.gr and/or ichachladakis@qu.edu.qa.

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Denis Sarigiannis,  
Aristotle University of Thessaloniki, Greece

## \*CORRESPONDENCE

Lucia Fazzo  
✉ lucia.fazzo@aiss.it

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# The health impact of hazardous waste landfills and illegal dumps contaminated sites: An epidemiological study at ecological level in Italian Region

Lucia Fazzo<sup>1,2\*</sup>, Valerio Manno<sup>3</sup>, Ivano Iavarone<sup>1,2</sup>, Giada Minelli<sup>3</sup>,  
Marco De Santis<sup>1,2</sup>, Eleonora Beccaloni<sup>1</sup>, Federica Scaini<sup>1</sup>,  
Edoardo Miotto<sup>4</sup>, Domenico Airoma<sup>5</sup> and Pietro Comba<sup>6</sup>

<sup>1</sup>Department of Environment and Health, Istituto Superiore di Sanità, Rome, Italy, <sup>2</sup>World Health Organization Collaborating Centre for Environmental Health in Contaminated Sites, Rome, Italy,

<sup>3</sup>Statistical Service, Istituto Superiore di Sanità, Rome, Italy, <sup>4</sup>Department of Medicine, University of

Udine, Udine, Italy, <sup>5</sup>Avellino Prosecution Office, Former North Naples Prosecution Office, Avellino, Italy,

<sup>6</sup>Fellow, Collegium Ramazzini, Bologna, Italy

**Background and aim:** The implementation of idoneous management of hazardous waste, in contrast to illegal practices, is one of the environment and health priorities of the WHO. The aim of the present study, based on a collaborative agreement between the Italian National Health Institute and a Prosecution Office located in Naples North, was to evaluate the health effects of illegal landfills and burning of urban and hazardous waste in the territory of the Prosecution Office.

**Methods:** The municipalities included in the study territory were investigated with respect to the regional population. Regression analyses were performed in the study area between four classes of an environmental municipal indicator of waste risk (MRI) previously defined, computing the relative risks (RRs) in 2–4 MRI classes, with respect to the first MRI class (the least impacted). The prevalence of reproductive outcomes and cause-specific mortality and hospitalization were analyzed in the general population and in the 0–19-year-old population using SAS software.

**Results:** An increase of mortality and hospitalization risk in both the genders of the whole area, with respect to regional population, were found for overall all cancer cases, cancer of the stomach, the liver, the lung and the kidney, and ischemic heart diseases. An increase of mortality for leukemias in the 0–19-year-old population and in hospitalization risk for certain conditions originating in the perinatal period were observed. Correlation between MRI and the risk of mortality from breast tumors in women (MRI class 2: RR = 1.06; MRI class 3: RR = 1.15; MRI class 4: RR = 1.11) and between MRI and the risk of hospitalization from testis tumors (MRI class 2: RR = 1.25; MRI class 3: RR = 1.31; MRI class 4: RR = 1.32) were found. The hospitalization risk from breast tumors and asthma exceeded significantly in both genders of three and four MRI classes. Among the 0–19-year-old population, correlation between MRI and hospitalization from leukemias (MRI class 2: RR = 1.48; MRI class 3: RR = 1.60; MRI class 4: RR = 1.41) and between MRI and the prevalence of preterm birth (MRI class 2: RR = 1.17; MRI class 3: RR = 1.08; MRI class 4: RR = 1.25) were found.

**Conclusion:** A correlation between health outcomes and the environmental pressure by uncontrolled waste sites was found. Notwithstanding the limitation of the study, the results promote implementing the actions of environmental remediation and the prosecution of illegal practices.

#### KEYWORDS

hazardous waste, landfills, dumps, mortality, hospitalization, cancer, low birth weight, preterm birth

## Introduction

Mismanaged and illegal waste sites are among the principal worldwide sources of soil and groundwater pollution. In the United States, the management of waste represents the main activity causing the contamination in the areas of the National Priority List of the Environmental Protection Agency (1), including 1,334 uncontrolled hazardous waste sites in March 2022 updating (<https://www.epa.gov/superfund/current-npl-updates-new-proposed-npl-sites-and-new-npl-sites>, last access 15 July 2022). In Europe, 38% of the contaminated sites are characterized by municipal and industrial waste disposals (2). The World Health Organization (WHO) included hazardous waste among the main environmental risk factors for the health population in Africa (3). In three Latin American countries (Mexico, Uruguay, and Argentina), 316,703 people were estimated to be exposed to the lead released by 129 hazardous waste sites (4). The WHO estimated that only 17.4% of the e-waste produced in 2019 reached formal waste management and recycling systems (5).

Uncontrolled and poorly managed industrial and hazardous waste landfills and illegal waste dumps could release and emit a mixture of environmental contaminants, often unknown, that are potentially dangerous for the health of the population residing close to these sites (6).

The increasing body of evidence about the possible health impact of environmental contamination due to waste mismanagement prompted the WHO to recommend the implementation of sustainable waste management practices, also contrasting illegal trafficking and management, among environment and health priorities to achieve the United Nations Sustainable Development Goals (7). The evidence of the association of several health effects with exposure to hazardous waste sites has been defined as “limited”: non-Hodgkin lymphoma; cancers of the liver, the bladder, the breast, and the testis; asthma; congenital anomalies overall and of the neural tube, the urogenital, connective, and musculoskeletal systems, and low weight and preterm birth, among reproductive outcomes. This evaluation, concerning articles published through 2015, was based on more than one study reporting strong and precise results, with an overall consistent association, though the authors could not completely exclude a role of random variability, bias, and confounding factors (8).

From January 2015 to May 2022, 16 additional articles on the human health impact of hazardous waste and dumping sites, including two studies on informal workers in waste sites, the so-called “pickers,” have been published (4, 9–23) [search in PubMed and Medline: (“industrial waste” [Mesh] OR

“hazardous waste” [Mesh] OR “waste disposal facilities” [Mesh] OR “electronic waste” [Mesh] OR “illegal dump\*” [Title/Abstract]) AND (“epidemiology” [all fields] OR “mortality” [all fields])]. The articles of interest were selected by two researchers who were blinded, among the 143 articles emerged from the search, based on compliance with the inclusion criteria (epidemiological studies on humans) and the search question, in terms of population/exposure/comparators/outcomes [population: resident population; exposure: living near hazardous and electronic waste sites and illegal dumps; comparators: all comparators; outcome: all diseases/health disorders (PECO)].

The majority of the selected articles concerns reproductive and childhood health outcomes. A systematic review published in 2017 highlighted the significantly elevated risk of preterm birth (PTB) among infants born to women living near hazardous waste sites and of congenital malformations in proximity to specific waste sites (10). Increased risks of low birth weight, intrauterine growth retardation, and vector-borne diseases, such as malaria, in the population living near dumps and burning waste sites, have been reported in a more recent review (22). An increase of very preterm birth, low and very low birth weight, and stillbirth were reported among mothers exposed to contaminants released by an illegal arson of a large municipal landfill during the periconception period and the first trimester (15). A population-based case-control study (9) found an increased risk of bone tumors in children (0–14 years old) living within 2 km of hazardous waste sites, and the impact of lead released by 129 hazardous waste sites in Latin American countries was estimated to be 51,432 DALYs for mild intellectual disability in children and cardiovascular disease in adults (4). An investigation performed on the acute effects consequently to an event of illegal dumping of tons of waste into a river in Malaysia reported shortness of breath, cough, nausea, vomiting, and eye and throat irritation in school children (6–17 years old) (23). An increase in mortality for all causes, specifically for all cancers and colon-rectum, bladder, and hematological tumors, in the general population (all ages) was reported by an ecological study in residents of a municipality with landfills (13). Some studies based on self-reported symptoms in the population living close to dumpsites and mismanaged landfills in low- and middle-income countries (LMICs) reported an increase in the prevalence of diabetes (19, 20), asthma, tuberculosis and depression (20), sore throat and hypertension (19), respiratory symptoms (wheezing and frequent sneezing), and skin rashes (21). Two biomonitoring investigations performed in Italian contaminated areas by illegal waste sites were recently published. The first one concerns a subarea of the so-called “Land of Fires” in the Campania Region, which is

characterized by a widespread presence of dumps and uncontrolled landfills (including waste burning sites): no correlation of persistent organic pollutants (POPs: PCBs, PCDDs, PBDEs, and PCDFs) and heavy metals blood concentration was observed with residence in the study area, but the highest values, also in comparison to the national average level, were reported in the municipality with the highest number of illegal and uncontrolled landfills (16). The importance of using private well water and consuming locally-bred eggs and beef in determining high blood levels of  $\beta$ -hexachlorocyclohexane ( $\beta$ -HCH) in the population residing within 1 km of the Sacco river, where illegal waste dumping occurred, was highlighted (18).

A special mention should be made of the articles on the health impact of electronic and electrical equipment, also known as “e-waste,” which has become an increasing problem in recent years, particularly in LMICs.

Some environmental monitoring studies observed high concentrations of heavy metals, dioxin-like compounds, and polycyclic hydrocarbons (PAHs) in e-waste sites (24–26), and some of the same compounds were also reported in blood or urine samples of the general population (27, 28), children (27, 29–34), and mothers (35, 36). Exposure to these components is reported in association with the alteration of fibrosis indicators (TGF- $\beta$  and  $\alpha$ -SMA) in the general population (27). Exposure to e-waste has been related to a high prevalence of childhood disorders: altered developmental measures (33, 35–37), neurodevelopment (30, 31, 38), behavioral disorders (38), anemia (29, 33), altered lung function (35, 37), and vascular inflammation and high blood pressure (34). In 2021, the WHO defined that prenatal and childhood e-waste exposure are significantly linked with specific birth and childhood health outcomes: impaired neurodevelopment and behavior, negative birth outcomes (including stillbirth, premature birth, shortened gestational age, low birth weight), lung functions and respiratory effects, impaired thyroid, cardiovascular and immune systems’ functions, including greater vulnerability to common infections and reduced response to immunization, DNA damage, and increased risk of some chronic diseases later in life (5). The review published in the same year was consistent with the WHO report, defining “suggestive” the association between these outcomes and e-waste exposure (39).

In this context, the present article describes a study aimed at estimating the health impact of residential exposure to uncontrolled landfills and illegal dumps in Italy, based on a collaborative agreement between the Italian National Health Institute (Istituto Superiore di Sanità: ISS) and the Naples North Prosecution Office (NNPO).

The study area (Figure 1) is the territory of NNPO, which includes 38 municipalities located between the Naples and Caserta provinces in the Campania Region (South Italy), and is characterized by a huge presence of waste sites (about 3,000 waste sites in 426 km<sup>2</sup>). Because of the environmental pressure due to the waste sites, the area is partially included among the contaminated sites of national concern for remediation. In addition, some subareas are included in the so-called “Land of Fires” national environmental emergency area, owing to illegal practices of waste open-air burning that have occurred since

the 2000s. Illegal waste trafficking and mismanagement by crime organizations in the area have been documented since the end of the 1980s based on crime organization exponents’ statements and judicial investigations. Industrial and urban waste, including those that are hazardous, have been illegally dumped in heaps, sunken, or buried in pits (illegal dumps), or disposed of in poorly managed landfills with no control (“uncontrolled” landfills) (40). Based on the European Legislation (Directive 91/689/EEC), transposed in Italian Legislation by means of Legislative Decree 152/06, the wastes are classified as hazardous, considering its origin, if it is known, the chemical–physical and toxicological characteristics of the substances potentially present in the waste itself. Before the cooperation agreement, both institutions had extensively investigated the area of interest. NNPO has been contrasting illegal practices of waste management since the early 1980s. ISS, in the meanwhile, had conducted a series of epidemiological studies on cancer mortality, cancer incidence, and prevalence of congenital anomalies at birth in the Provinces of Naples and Caserta in relation to waste contamination (41–44).

The first step of the collaborative study consisted in the implementation of a geo-database of the waste sites and the development of a GIS-based indicator of waste risk (40). In the study area, which is 426 km<sup>2</sup> large, 2,767 waste sites, including illegal waste burning, were mapped and characterized on the basis of the environmental data and information available at the beginning of the investigation. A total of 38% of the population was estimated to be living within 100 m of one or more waste sites, areas potentially impacted by the contaminants emitted or released by the waste sites. The choice of a large buffer of 100 m around the waste site to identify the potentially impacted areas, relatively short with respect to those of 1–2 km used in other similar contexts, was due to the high density of waste sites in the study area. The data sources, including information collected by the Prosecutor through judiciary inquiries, considered the waste sites identified in the 2008–2017 period; at the beginning of the investigation, significant remediation acts have not yet been carried out. The method used to assign the index of waste risk to each municipality (municipal waste risk index: MRI) was described in the article previously published (40). A hazard risk quantification (hazard risk level: HRL) was attributed by experts’ knowledge to each of the 2,767 waste sites on the basis of the information available for all sites: modality of waste disposal (i.e., illegal burning sites and dumps, controlled landfills and treatment plants, temporary storage), characteristics of the site, environmental contaminants present in the site, and type of waste. The highest level of HR was attributed to the 653 burning waste sites based on the possible contamination of all environmental media (air, soil, and water). There was no information on the duration of the fires, but the sporadic ones reported by individuals were not considered: the included sites concern arsons of waste heaps, plastic, and temporary waste storage that occurred between 2011 and 2018, as documented by law enforcement and regional institutions. To follow, no visible dumps (sunken or buried) of potentially hazardous and highly hazardous waste were considered very high-impacting waste sites. Based on the site HRL and on the estimated population residing in each impacted area (within 100 m of one or more waste sites),



FIGURE 1  
Area at study.

a municipal waste risk index (municipal risk index: MRI) was computed; the 38 municipalities were then categorized into four classes of MRI (1–low to 4–high) (details provided in the original article) (40).

The present contribution assesses the health profile of populations living in the territory of NNPO, as compared to the regional population and presents results of the regression analyses linking the risk from selected health outcomes to the municipal environmental waste risk indicator (MRI) within the study area to estimate the health impact of uncontrolled and illegal waste management in the territory of Naples North Prosecution Office jurisdiction.

In particular, cause-specific mortality and hospitalization and birth certificates in the population living in the study area were

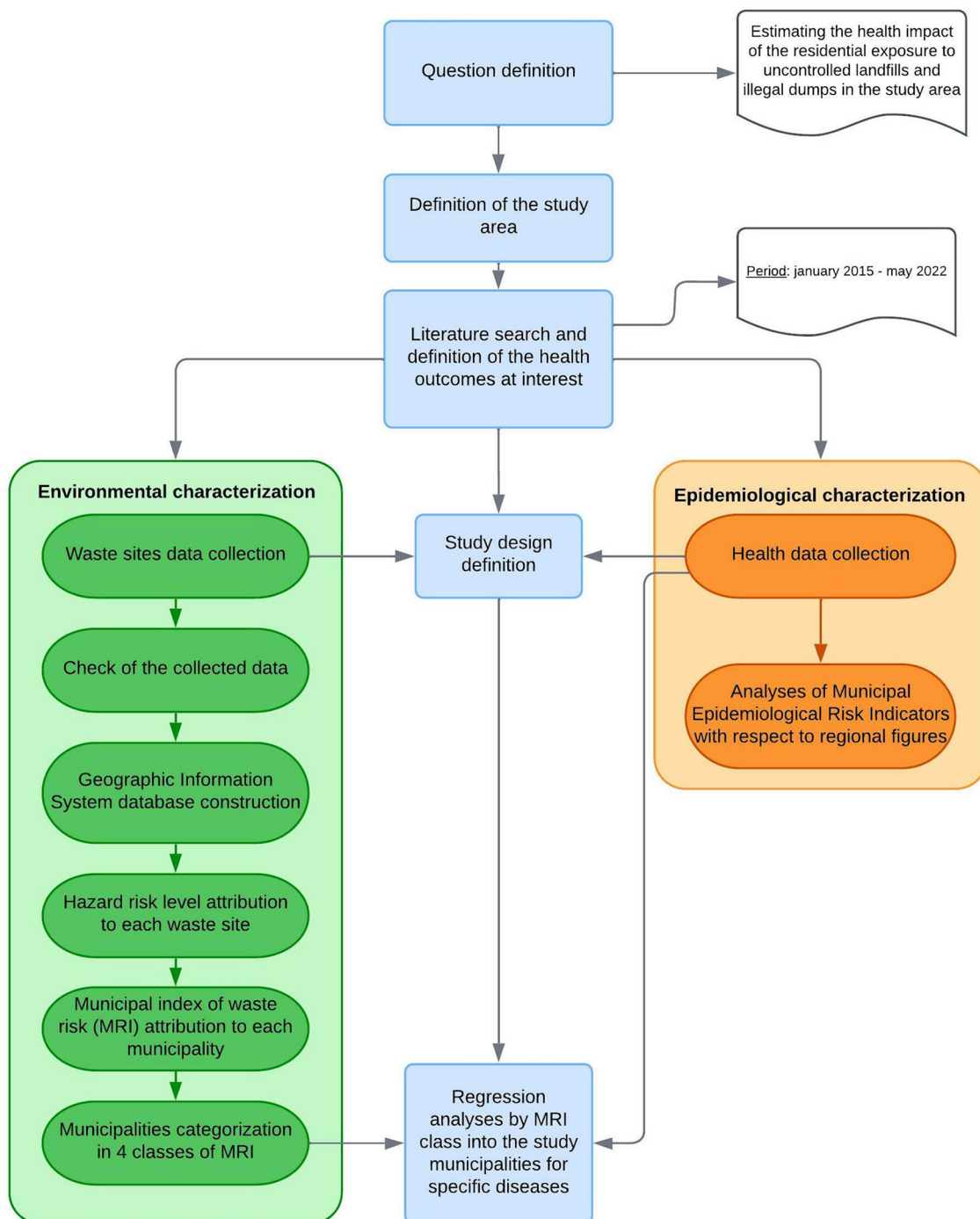
analyzed, and the possible correlation with the environmental waste risk indicator, previously elaborated, was evaluated.

## Materials and methods

The sequential steps of the study are summarized in the methodology flow chart (Figure 2).

The diseases of interest for the aim of the investigation were selected *a priori*, considering the abovementioned review on the health impact of hazardous waste (8) and the toxicological literature on the contaminants reported in the waste sites of the study area.

We analyzed the municipal mortality and hospitalization database (2008–2019 period) available at the Statistics Office of



the National Institute for Health, based on the Italian National Institute of Statistics (ISTAT) and Ministry of Health data, respectively. We considered the main cause reported in the death certificate and the principal diagnosis of the hospitalization discharge. For cancer diseases, a *wash-out* period up to 2001 was considered to estimate the first hospitalization, while the first hospitalization during the 2008–2019 period was considered for the other hospitalization diagnoses. For each selected disease,

we analyzed the more informative outcome on the basis of the etiopathogenic characteristics.

In addition, we analyzed the birth assistance certificate (2003–2017 period) provided by the Ministry of Health to estimate the risk of low birth weight (LBW, born alive with weight <2,500 gr) and of preterm birth (PTB, born alive with gestational age < 37 weeks). The analyses of the prevalence of PTB excluded twins and the analyses of LBW excluded PTBs and twins.

## Overall study area with respect to the regional population

To evaluate the health status of the population residing in the overall study area (38 municipalities combined), we computed the gender-specific standardized mortality and hospitalization ratios (SMR and SHR) for selected diseases with respect to the regional population, excluding the residents in the study area. The analyses were performed both for the general population (all ages) and for specific age classes (0–1 and 0–19 years).

For LBW and PTB, we computed the ratio of prevalence (percentage of overall born alive) in study areas vs. the prevalence in the referent population (Campania Region, excluding the 38 municipalities in the study).

## Regression analysis into the study area by MRI class

In the previous study, the municipalities were categorized into four MRI classes (increasing waste risk from 1 to 4 MRI classes) on the basis of environmental characterization of the waste sites and the population living within 100 m of one or more waste sites (40).

Details on the used method to compute MRI were described in the original article. The principal steps are reported further in this study. Afterward, the attribution of a hazard risk level to each waste site, following the criteria described in the Introduction section, the population living within 100 m to one or more waste sites was estimated.

To achieve this goal, the layers of the waste sites and those of the census tract sections were combined in GIS software: a new layer consisting of about 26,000 polygons was generated.

A multi-code HRL (equal to the sum of HRLs) was attributed to the areas influenced by more than one site, with an *ad hoc* procedure. The population living in the areas impacted by waste was estimated on the basis of the density of the population in the census tract where the polygon falls. For each polygon, a risk index (RI) was computed.

$$RI = S * HRL * S/Sc * P,$$

where S is the surface of the polygon, HRL is the hazard risk level index of the waste site, or the multi-code HRL of the waste sites, lying in the polygon, Sc is the surface of the census tract, P is the population residing in the census tract,  $S/Sc \times P$  is the estimated population residing in the polygon, and RI is proportional to the population living in the census tract: for an inhabited census tract, the RI is equal to 0.

Subsequently, the waste risk index at the municipal level (municipal risk index: MRI) was computed, summing up the scores of all areas (polygons) comprising the municipality.

$$MRI = \sum_{p=1}^n RI_p,$$

where  $p$  is the number of polygons lying in the municipality and  $RI_p$  is the risk index of polygons lying in the municipality.

Finally, the 38 municipalities were categorized into four classes of MRI (1–low to 4–high), using Jenks' method (natural breaks) to maximize homogeneity within groups and variance between groups (40).

In the present investigation, regression analyses by MRI class into the 38 municipalities of the study area were performed for the diseases recognizing waste exposure among the risk factors with evidence defined limited (8). The relative risks (RR, 90% confidence interval) in MRI classes 2, 3, and 4 with respect to MRI class 1, composed of the municipalities less impacted by the waste sites, were computed. A generalized linear model was applied, using SAS software 9.4 version.

The analyses were performed in the general population and in the 0–19-year-old population for specific outcomes.

## Results

### Overall study area with respect to the regional population

The study area is constituted of 38 municipalities, 426 km<sup>2</sup> large, with 973,509 inhabitants (2019 Census). The area is located in the Campania Region (Southern Italy), between Naples and Caserta Provinces, partially included in a contaminated site of national concern for remediation ("Domitio-flegreo e agro Aversano") and in the so-called "Land of Fires," because of the presence of illegal waste burning sites (Figure 1). In the area, 2,767 waste sites, including illegal waste burning (653 sites), were mapped and 38% of the population was estimated to living within 100 m of one or more waste sites (40).

Tables 1, 2 report the results of the analyses of mortality and hospitalization risks for the investigated diseases (SMRs and SHRs) in the general population living in the study area, by gender. The whole study area showed an increase in mortality and hospitalization, with respect to the regional population, in both genders, for overall malignant tumors, particularly for cancers of the stomach, the liver, the lung, and the kidney and for ischemic heart diseases. Exceeding mortality in men and women was observed also for skin melanoma and chronic liver diseases and cirrhosis. In addition, hospitalization was higher in both genders for larynx, bladder, and thyroid gland cancers, dementia, Alzheimer's disease, and acute myocardial infarction. Breast cancer was exceeding in women, both in terms of both mortality and hospitalization.

The analyses focusing on pediatric-adolescent subpopulations showed an increase in mortality for leukemias in the 0–19-year-old population and in hospitalization for certain conditions originating in the perinatal period (Tables 3, 4).

The prevalence of PTB and LBW was significant higher in the whole area with respect to the regional population (Table 5).

### Regression analysis into the study area by MRI class

The distribution of municipalities and population by MRI class is reported in Supplementary Table 1.

TABLE 1 Mortality in the general population in the whole area, by gender. 2008–2019 period.

| ICD-10 code      | Mortality cause                                                                                        | Men    |               | Women |               |
|------------------|--------------------------------------------------------------------------------------------------------|--------|---------------|-------|---------------|
|                  |                                                                                                        | Obs    | SMR (90% CI)  | Obs   | SMR (90% CI)  |
| C00–C97          | Malignant neoplasms                                                                                    | 14,566 | 121 (120–123) | 9,857 | 116 (114–118) |
| C16              | Malignant neoplasm of stomach                                                                          | 918    | 142 (135–150) | 615   | 138 (129–147) |
| C22              | Malignant neoplasm of liver and intrahepatic bile ducts                                                | 1,382  | 142 (136–148) | 766   | 156 (147–166) |
| C25              | Malignant neoplasm of pancreas                                                                         | 613    | 110 (103–118) | 541   | 104 (97–111)  |
| C32              | Malignant neoplasm of larynx                                                                           | 347    | 146 (134–159) | 37    | 115 (88–150)  |
| C33–C34          | Malignant neoplasm of trachea, bronchus, and lung                                                      | 4,706  | 132 (129–135) | 1,274 | 117 (112–122) |
| C43              | Malignant melanoma of skin                                                                             | 163    | 123 (108–140) | 130   | 127 (110–146) |
| C45.0            | Mesothelioma of pleura                                                                                 | 64     | 99 (80–121)   | 25    | 134 (96–186)  |
| C49              | Malignant neoplasm of other connective and soft tissue                                                 | 51     | 90 (72–113)   | 42    | 85 (66–110)   |
| C50              | Malignant neoplasm of breast                                                                           | 20     | 122 (85–176)  | 1,639 | 110 (105–114) |
| C61              | Malignant neoplasm of prostate                                                                         | 846    | 101 (95–107)  |       |               |
| C62              | Malignant neoplasm of testis                                                                           | 17     | 88 (59–131)   |       |               |
| C64, C66, C68    | Malignant neoplasms of kidney, ureter, and other unspecified urinary organs                            | 344    | 120 (110–131) | 174   | 131 (116–149) |
| C67              | Malignant neoplasm of bladder                                                                          | 899    | 130 (123–137) | 167   | 105 (92–119)  |
| C70–C72, D33     | Malignant neoplasms of central nervous system                                                          | 324    | 102 (93–112)  | 258   | 109 (98–121)  |
| C73              | Malignant neoplasm of thyroid gland                                                                    | 36     | 118 (90–155)  | 29    | 72 (53–97)    |
| C81–C96          | Malignant neoplasms, stated or presumed to be primary, of lymphoid, haematopoietic, and related tissue | 943    | 101 (96–107)  | 763   | 101 (96–108)  |
| C82–C85          | Non-Hodgkin lymphomas                                                                                  | 309    | 100 (91–110)  | 249   | 105 (95–117)  |
| C91–C95          | Leukaemias                                                                                             | 418    | 105 (97–114)  | 308   | 95 (87–105)   |
| C91              | Lymphoid leukemia                                                                                      | 119    | 95 (82–110)   | 87    | 95 (80–114)   |
| C92              | Myeloid leukemia                                                                                       | 78     | 91 (75–109)   | 71    | 99 (82–121)   |
| G12.2            | Motor neuron disease                                                                                   | 70     | 78 (64–95)    | 64    | 91 (74–112)   |
| J18, J20–J22     | Acute respiratory diseases                                                                             | 229    | 97 (87–109)   | 214   | 97 (86–108)   |
| I20–I25          | Ischaemic heart diseases                                                                               | 5,212  | 110 (108–113) | 5,017 | 123 (120–126) |
| I21              | Acute myocardial infarction                                                                            | 1,775  | 89 (86–92)    | 1,291 | 98 (94–103)   |
| N00–N08, N17–N19 | Glomerular diseases and renal failure                                                                  | 589    | 99 (93–106)   | 798   | 124 (117–131) |
| K71–K74          | Chronic liver diseases and cirrhosis                                                                   | 852    | 117 (110–124) | 825   | 145 (137–154) |

ICD-10, International Classification of Diseases 10th revision; obs, observed cases; SMR, standardized mortality ratio; CI, confidence interval.

Tables 6, 7 show the RR of the mortality and hospitalization, respectively, by MRI class, using class 1 (the municipalities lowest impacted by waste) as a reference, and gender.

The mortality for breast and liver tumor was higher in female subjects of MRI classes 2, 3, and 4, with lower confidence interval values between 0.85 and 1.03; the mortality rate for bladder cancer was higher in men living in MRI class 4 (Table 6).

The hospitalization rate for breast cancer was higher in men and women living in MRI classes 2 (with lower CI limits <1), 3, and 4; in MRI classes 3 and 4, the hospitalization rate for asthma also increases. Exceeding hospitalization for testis cancer was observed in all MRI classes 2–4 with respect to class 1 (Table 7).

Table 8 shows the results of the hospitalization regression analyses in the 0–19-year-old population, and Table 9 reports the RR of PTB and LBW. Among the 0–19-year-old population, the hospitalization rate for all leukemias was higher in MRI classes 2–4, for asthma in the last two classes (MRI classes 3 and 4), and for acute respiratory diseases in the class most impacted by waste (MRI class 4) (Table 8). No increase of LBW risk was detected by MRI class, meanwhile the risk of PTB exceeds in MRI classes 2–4 (Table 9).

Figures 3–5 show the forest plots of the main results; all forest plots of the regression analyses are reported in Supplementary Figures 1–10.

TABLE 2 Hospitalization in the general population in the whole area, by gender. 2008–2019 period.

| ICD-9 CM code                | Hospitalization cause                                                 | Men    |               | Women  |               |
|------------------------------|-----------------------------------------------------------------------|--------|---------------|--------|---------------|
|                              |                                                                       | Obs    | SHR (90% CI)  | Obs    | SHR (90% CI)  |
| 140–208                      | Malignant neoplasms                                                   | 26,774 | 108 (107–109) | 23,443 | 103 (102–104) |
| 151                          | Malignant neoplasm of stomach                                         | 1,197  | 136 (130–143) | 769    | 129 (121–137) |
| 155                          | Malignant neoplasm of liver and intrahepatic bile ducts               | 1,634  | 125 (120–130) | 812    | 134 (127–142) |
| 157                          | Malignant neoplasm of pancreas                                        | 625    | 104 (97–111)  | 537    | 100 (93–107)  |
| 161                          | Malignant neoplasm of larynx                                          | 853    | 127 (120–135) | 152    | 150 (131–171) |
| 162                          | Malignant neoplasm of trachea, bronchus, and lung                     | 4,535  | 125 (122–128) | 1,391  | 113 (108–118) |
| 172                          | Malignant melanoma of skin                                            | 631    | 115 (107–122) | 604    | 106 (99–113)  |
| 163                          | Malignant neoplasm of pleura                                          | 147    | 103 (90–118)  | 55     | 99 (79–123)   |
| 171                          | Malignant neoplasm of connective and other soft tissue                | 273    | 95 (86–105)   | 218    | 97 (87–108)   |
| 174–175                      | Malignant neoplasm of female and male breast                          | 91     | 139 (117–166) | 6,537  | 99 (97–101)   |
| 185                          | Malignant neoplasm of prostate                                        | 2,791  | 86 (84–89)    |        |               |
| 186                          | Malignant neoplasm of testis                                          | 496    | 101 (94–109)  |        |               |
| 189                          | Malignant neoplasm of kidney and other and unspecified urinary organs | 1,241  | 113 (108–119) | 604    | 113 (105–121) |
| 188                          | Malignant neoplasm of bladder                                         | 4,072  | 114 (111–117) | 918    | 111 (105–117) |
| 191–192                      | Malignant neoplasm of central nervous system                          | 623    | 94 (88–100)   | 508    | 92 (86–99)    |
| 193                          | Malignant neoplasm of thyroid gland                                   | 488    | 107 (100–116) | 1,469  | 104 (100–109) |
| 200–208                      | Malignant neoplasm of lymphatic and hematopoietic tissue              | 2,393  | 101 (98–104)  | 2,006  | 102 (98–106)  |
| 200, 202                     | Non-Hodgkin lymphomas                                                 | 1,190  | 102 (97–106)  | 995    | 103 (98–109)  |
| 204–208                      | Leukemias                                                             | 835    | 103 (97–109)  | 638    | 104 (98–111)  |
| 204                          | Lymphoid leukemia                                                     | 380    | 99 (91–107)   | 282    | 102 (93–113)  |
| 205                          | Myeloid leukemia                                                      | 447    | 105 (97–113)  | 333    | 97 (89–106)   |
| 250                          | Diabetes mellitus                                                     | 3,499  | 86 (83–88)    | 3,025  | 91 (88–94)    |
| 290.0, 290.4,<br>331.1–331.2 | Dementias                                                             | 449    | 133 (123–143) | 545    | 123 (115–132) |
| 331.0                        | Alzheimer's disease                                                   | 156    | 90 (79–102)   | 264    | 87 (78–96)    |
| 332                          | Parkinson's disease                                                   | 455    | 85 (79–92)    | 324    | 82 (75–90)    |
| 335.2                        | Motor neuron disease                                                  | 142    | 92 (80–105)   | 112    | 103 (88–121)  |
| 460–466, 480–487             | Acute respiratory diseases                                            | 12,113 | 82 (81–83)    | 9,319  | 81 (79–82)    |
| 493                          | Asthma                                                                | 2,875  | 88 (86–91)    | 2,432  | 85 (82–88)    |
| 410–414                      | Ischemic heart disease                                                | 23,902 | 102 (101–103) | 11,079 | 109 (107–111) |
| 410                          | Acute myocardial infarction                                           | 11,749 | 115 (113–117) | 5,204  | 124 (121–127) |
| 580–586                      | Nephritis, nephrotic syndrome, nephrosis, renal failure included      | 5,115  | 95 (93–97)    | 4,354  | 105 (102–107) |
| 571                          | Chronic liver disease and cirrhosis                                   | 5,275  | 92 (90–94)    | 3,663  | 101 (98–103)  |

ICD-9 CM, International Classification of Diseases 9th revision Clinical Modification; obs, observed cases; SHR, standardized hospitalization ratio; CI, confidence interval.

## Discussion

The study area was characterized by a huge presence of waste sites (2,767 waste sites in 426 km<sup>2</sup>) and illegal practices of waste management (characterizing ~90% of the waste sites)

that occurred in the area since the early 1980s and was documented to be present in the 2008–2017 period (Figure 6). At the beginning of the present investigation, no significant environmental remediation actions have been performed. The analyses of the health profile of the population residing in the

**TABLE 3** Mortality in the whole area, in 0–19 age class, males and females combined. 2008–2019 period.

| Age class         | ICD-10 code  | Mortality cause                                        | Obs | SMR (90% CI)  |
|-------------------|--------------|--------------------------------------------------------|-----|---------------|
| <b>0–19 years</b> |              |                                                        |     |               |
|                   | A00–T98      | All causes                                             | 777 | 94 (89–100)   |
|                   | C00–D48      | All neoplasms                                          | 96  | 99 (84–117)   |
|                   | C70–C72, D33 | Malignant neoplasms central nervous system             | 17  | 84 (56–125)   |
|                   | C81–C96      | Malignant neoplasms of lymphohaematopoietic system     | 29  | 114 (84–154)  |
|                   | C91–C95      | All leukaemias                                         | 26  | 141 (102–195) |
|                   | C49          | Malignant neoplasm of other connective and soft tissue | 2   | 49 (16–148)   |
| <b>0–1 year</b>   |              |                                                        |     |               |
|                   | A00–T98      | All causes                                             | 423 | 97 (89–105)   |
|                   | C00–D48      | Neoplasms                                              | 7   | 135 (73–248)  |
|                   | C70–C72, D33 | Malignant neoplasms of central nervous system          | 0   |               |
|                   | C81–C96      | Malignant neoplasms of lymphohaematopoietic system     | 1   | 135 (30–603)  |
|                   | P00–P96      | Certain conditions originating in the perinatal period | 241 | 95 (86–106)   |

ICD-10, International Classification of Diseases 10th revision; obs, observed cases; SMR, standardized mortality ratio; CI, confidence interval.

**TABLE 4** Hospitalization in the whole area, in 0–19 age class, males and females combined. 2008–2019 period.

| Age class         | ICD-9CM code     | Hospitalization cause                                  | Obs    | SHR (90% CI)  |
|-------------------|------------------|--------------------------------------------------------|--------|---------------|
| <b>0–19 years</b> |                  |                                                        |        |               |
|                   | 460–466; 480–487 | Acute respiratory diseases                             | 11,206 | 77 (76–78)    |
|                   | 493              | Asthma                                                 | 3,819  | 94 (92–97)    |
|                   | 580–586          | Nephritis, nephrotic syndrome, and nephrosis           | 711    | 104 (98–111)  |
| <b>0–1 year</b>   |                  |                                                        |        |               |
|                   | 760–779          | Certain conditions originating in the perinatal period | 10,189 | 101 (100–103) |

ICD-9 CM, International Classification of Diseases 9th revision Clinical Modification; obs, observed cases; SHR, standardized hospitalization ratio; CI, confidence interval.

**TABLE 5** Prevalence of preterm and low birth weight, in the whole area. Males and females combined. 2013–2017 period.

|                    | Obs   | % obs/born alive | RP (90% CI)   |
|--------------------|-------|------------------|---------------|
| Preterm birth*     | 2,870 | 3.71             | 106 (102–110) |
| Low birth weight** | 1,551 | 6.42             | 108 (103–113) |

Obs, observed cases; RP, ratio of prevalence; CI, confidence interval; \*excluding twins; \*\*excluding preterm birth and twins.

study area show some relevant criticalities as compared to the general population of the Campania Region. Most of the excesses are, moreover, detected in both genders, supporting the role of environmental exposures.

The present investigation shows a correlation, at the municipal level, between the indicator of the environmental risk impact of the waste site (MRI) and specific health outcomes: breast and testis cancers and asthma in the general population, leukemias in the 0–19-year-old subpopulation, and the prevalence of preterm birth. The municipalities belonging to the highest MRI classes (classes 3 and 4) are characterized by illegal and uncontrolled dumps of hazardous waste, including sites where illegal waste burning occurred. Moreover, as above mentioned, in the study area

significant environmental cleanup acts have not been carried out, at the beginning of the present investigation.

Some further considerations are needed in order to interpret the results.

The ecological study design at the municipal level does not allow inferring risks at the individual level but could represent a useful indicator of risks playing at the population level to identify appropriate interventions for public health (45). The assessment of exposure based on residence at the municipal level may cause a bias in the estimates, which, causing non-differential exposure misclassification, results in an underestimation of the risks (46); this issue has been addressed by several authors (47, 48), and Jurek et al. advised the use of sensitivity analysis to evaluate the measures of underestimation if local data are available (49). However, it should also be considered that the municipal environmental waste risk indicator (MRI) was built considering the populations living in the census tracts near the waste sites (40).

The regression analysis was performed among municipalities included in an area extensively impacted by waste sites, where increases in mortality rate and hospitalization for some outcomes, with respect to the regional reference, were detected.

TABLE 6 Mortality, 2008–2019. Relative risk (RR), by gender and class of municipal environmental indicator of waste risk (MRI).

| Diseases                      | MRI class 1 |       | MRI class 2      |                  | MRI class 3      |                  | MRI class 4      |                  |
|-------------------------------|-------------|-------|------------------|------------------|------------------|------------------|------------------|------------------|
|                               | Men         | Women | Men              | Women            | Men              | Women            | Men              | Women            |
|                               | RR          | RR    | RR (90% CI)      | RR (90% CI)      | RR (90% CI)      | RR (90% CI)      | RR (90% CI)      | RR (90% CI)      |
| Malignant tumor (MT) of liver | 1           | 1     | 1.17 (1.05–1.30) | 1.16 (1.00–1.35) | 0.99 (0.88–1.12) | 1.17 (1.00–1.38) | 0.91 (0.79–1.06) | 1.03 (0.85–1.25) |
| MT of breast                  | 1           | 1     | 1.19 (0.48–2.99) | 1.06 (0.95–1.17) | 1.05 (0.37–2.95) | 1.15 (1.03–1.28) | 1.08 (0.35–3.35) | 1.11 (0.98–1.25) |
| MT of testis                  | 1           |       | 1.32 (0.45–3.73) |                  | 1.76 (0.62–5.00) |                  | 0.91 (0.23–3.61) |                  |
| MT of bladder                 | 1           | 1     | 0.87 (0.75–1.00) | 0.73 (0.52–1.03) | 1.00 (0.86–1.16) | 1.26 (0.92–1.73) | 1.18 (1.00–1.39) | 0.81 (0.53–1.24) |
| Non-Hodgkin lymphoma          | 1           | 1     | 1.03 (0.81–1.32) | 1.12 (0.87–1.44) | 1.49 (1.17–1.89) | 0.72 (0.52–0.98) | 1.06 (0.78–1.42) | 0.95 (0.68–1.31) |

CI, confidence interval.

TABLE 7 Hospitalization, 2008–2019. Relative risk (RR), by gender and class of municipal environmental indicator of waste risk (MRI).

| Diseases                      | MRI class 1 |       | MRI class 2      |                  | MRI class 3      |                  | MRI class 4      |                  |
|-------------------------------|-------------|-------|------------------|------------------|------------------|------------------|------------------|------------------|
|                               | Men         | Women | Men              | Women            | Men              | Women            | Men              | Women            |
|                               | RR          | RR    | RR (90% CI)      | RR (90% CI)      | RR (90% CI)      | RR (90% CI)      | RR (90% CI)      | RR (90% CI)      |
| Malignant tumor (MT) of liver | 1           | 1     | 1.07 (0.97–1.18) | 1.14 (0.99–1.31) | 0.95 (0.85–1.06) | 1.12 (0.96–1.31) | 0.82 (0.72–0.94) | 0.74 (0.61–0.91) |
| MT of breast                  | 1           | 1     | 1.48 (0.88–2.48) | 1.02 (0.97–1.07) | 2.61 (1.62–4.21) | 1.07 (1.01–1.13) | 2.62 (1.56–4.37) | 1.05 (0.99–1.12) |
| MT of testis                  | 1           |       | 1.25 (1.03–1.51) |                  | 1.31 (1.07–1.61) |                  | 1.32 (1.06–1.65) |                  |
| MT of bladder                 | 1           | 1     | 0.94 (0.88–1.01) | 0.92 (0.80–1.06) | 0.99 (0.92–1.06) | 1.20 (1.04–1.38) | 0.93 (0.86–1.01) | 1.03 (0.87–1.22) |
| Non-Hodgkin Lymphoma          | 1           | 1     | 0.95 (0.83–1.07) | 1.02 (0.89–1.16) | 1.10 (0.97–1.25) | 0.94 (0.82–1.09) | 1.07 (0.92–1.23) | 1.02 (0.87–1.19) |
| Asthma                        | 1           | 1     | 0.96 (0.90–1.05) | 1.00 (0.91–1.09) | 1.15 (1.06–1.25) | 1.28 (1.17–1.40) | 1.28 (1.17–1.40) | 1.23 (1.11–1.35) |

CI, confidence interval.

TABLE 8 Hospitalization, 2008–2019. Zero to nineteen years old. Males and females combined. Relative risk (RR), by class of municipal environmental indicator of waste risk (MRI).

| Causes                     | MRI class 1 | MRI class 2      | MRI class 3      | MRI class 4      |
|----------------------------|-------------|------------------|------------------|------------------|
|                            | RR          | RR (90% CI)      | RR (90% CI)      | RR (90% CI)      |
| All malignant tumors       | 1           | 1.16 (1.00–1.34) | 1.14 (0.97–1.33) | 0.90 (0.75–1.08) |
| Leukemias overall          | 1           | 1.48 (1.08–2.03) | 1.60 (1.15–2.23) | 1.41 (0.98–2.02) |
| Acute respiratory diseases | 1           | 1.02 (0.98–1.07) | 0.94 (0.90–0.99) | 1.19 (1.14–1.25) |
| Asthma                     | 1           | 0.98 (0.92–1.05) | 1.18 (1.10–1.27) | 1.31 (1.21–1.41) |

CI, confidence interval.

Spatial autocorrelation between the analyzed municipalities was not taken into account, considering that the whole area is highly impacted by waste sites. This assumption could entail bias in the estimations (50); nevertheless, the present investigation aimed to analyze the risk of health outcomes as a function of the environmental indicator,

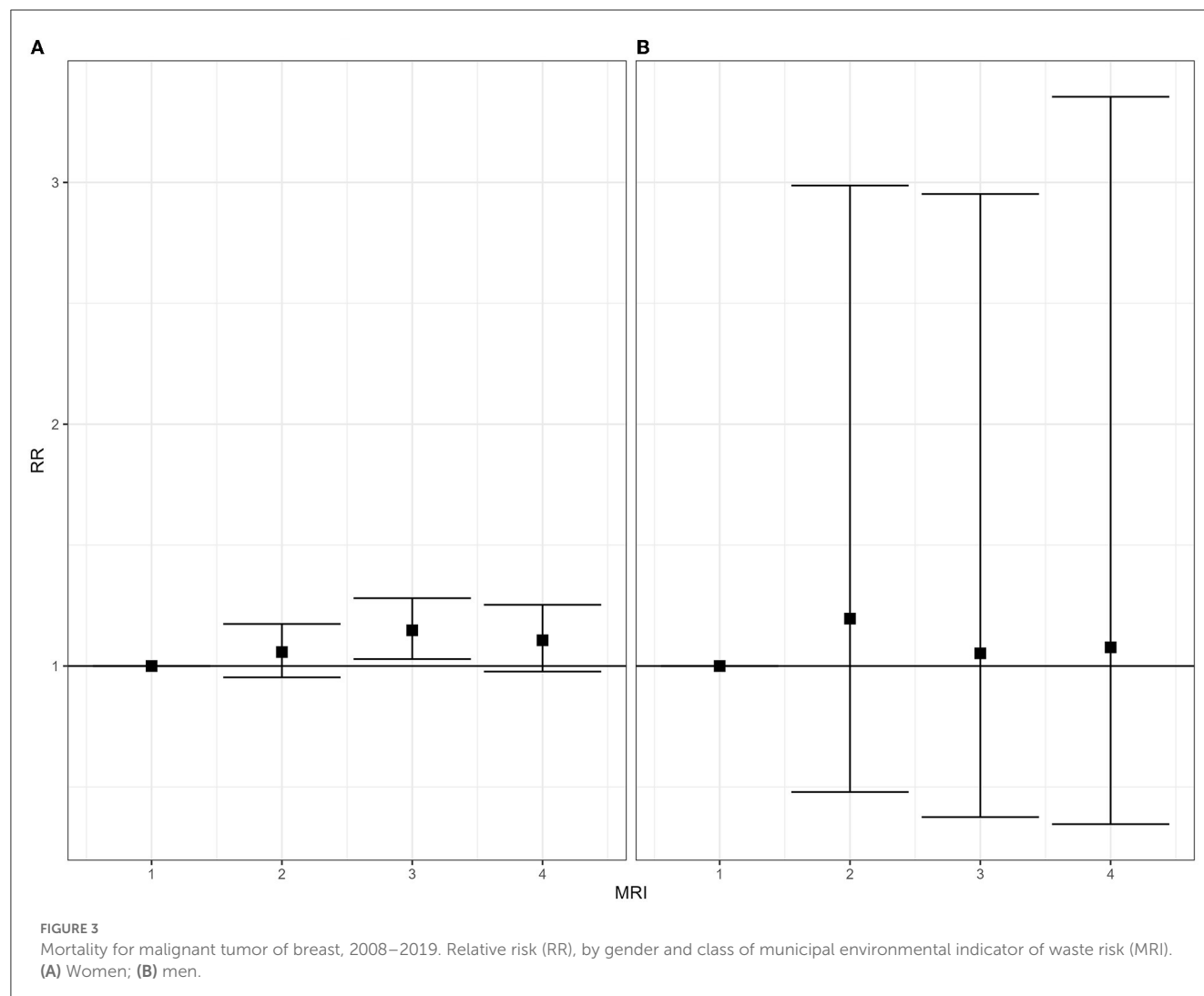
highlighting the individual municipalities with higher levels of criticality.

Some biomonitoring investigations have been performed in the so-called “Land of Fires” (51–54), which includes our study area. The medium concentrations of PCB and dioxin-like agents in cow’s and mother’s milk were consistent with the national

**TABLE 9** Prevalence at birth, 2013–2017. Males and females combined. Relative risk (RR), by Class of municipal environmental indicator of waste risk (MRI).

|                   | MRI class 1 | MRI class 2      | MRI class 3      | MRI class 4      |
|-------------------|-------------|------------------|------------------|------------------|
|                   | RR          | RR (90% CI)      | RR (90% CI)      | RR (90% CI)      |
| Low birth weight* | 1           | 0.94 (0.84–1.05) | 1.00 (0.89–1.13) | 1.01 (0.89–1.14) |
| Preterm birth**   | 1           | 1.17 (1.08–1.27) | 1.08 (0.99–1.18) | 1.25 (1.14–1.37) |

CI, confidence interval; \*excluding twins; \*\*excluding preterm birth and twins.

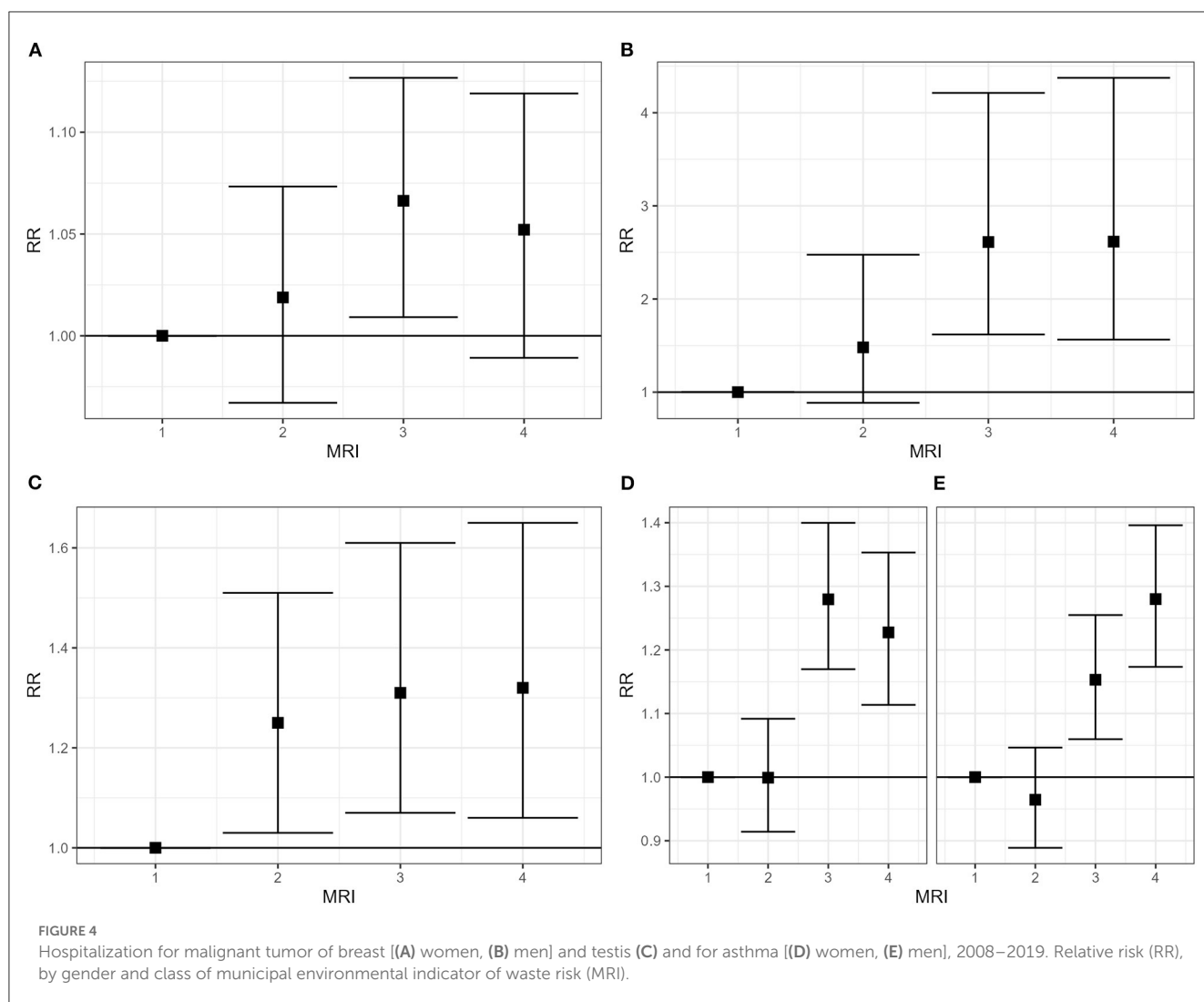


values, detecting individual high values in specific subareas, in some cases characterized by uncontrolled and illegal dumps and burning waste sites (50–53). A more recent study mentioned in the Introduction paragraph did not observe an association between POPs (PCBs, PCDDs, PBDEs, and PCDFs) and heavy metals blood concentrations with residence in the “Land of Fires,” but the highest values were observed in the municipality with the highest presence of waste sites (16), which coincided with one of the municipalities included in the highest MRI class in the present investigation.

Class 1 of MRI, used as a reference in the regression analyses, includes municipalities with an ascertained impact of waste sites, even if lower than the other ones. The analyses of

this class, when compared to the regional population, showed an increase in both genders of mortality and hospitalization for liver and bladder cancer as well as of mortality from breast tumor; in addition, the prevalence of LBW was higher than expected (Supplementary Tables 2–4). The choice of this reference class, not to be considered as unexposed, was due to data availability and could be a limitation of the study design; however, this is expected to increase the likelihood of the exceeding risks observed in municipalities with higher MRI values.

Because of the unavailability of cancer incidence data, we analyzed the occurrence of oncological diseases through the



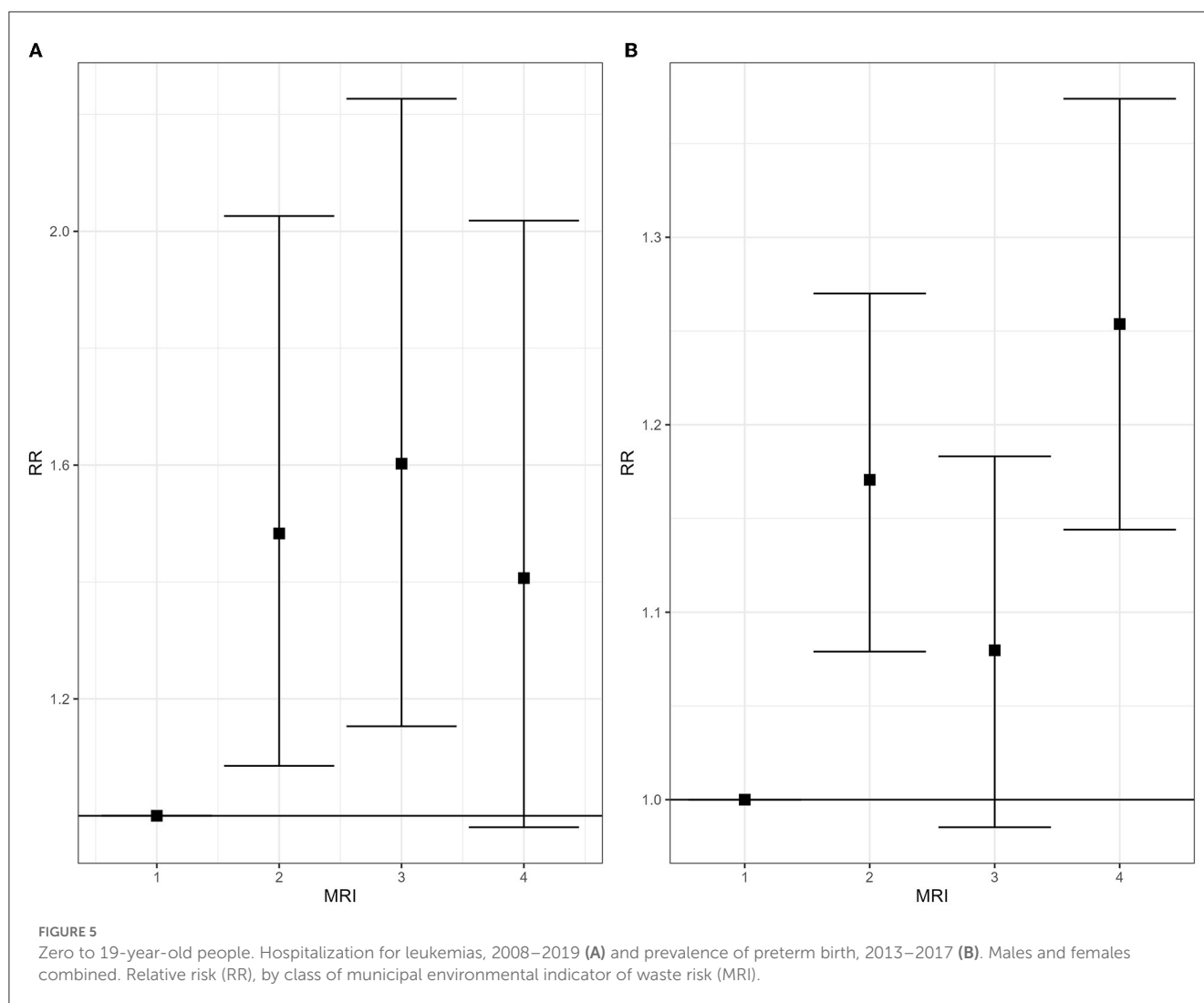
hospital discharge records. The limitation of the use of these data to estimate the incidence of cancers is largely documented, and the results represent the risk of hospitalization for the considered tumors, even if the *wash out* period used in the selection of the hospital discharge records for these diseases could reduce the bias of the estimates. In addition to cancer registries data, which are the gold standard for assessing cancer incidence in a population, hospital discharge records could be useful in the active search for cancer cases (55). An integration of mortality and hospital discharge data with those of the cancer and congenital anomalies registries is, therefore, advisable, and an evaluation of the feasibility of further study developments is ongoing.

In addition, we did not have information on any waste site located outside the study area, and an underestimation of the waste sites' impact could affect the neighboring municipalities in particular.

The present investigation aimed to highlight the waste sites with a possible health impact on the population. In the analyses, we did not consider other risk factors because of the study design and the availability of data. The investigated diseases, even if selected on the basis of the evidence of association

with exposure to substances released by the waste sites, have a multifactorial etiology, and the exposure to waste sites could concur with their occurrence. However, the regression analysis was performed among populations living in the restricted study area, likely similar in terms of socio-economic status, access to health services, environmental exposures, and lifestyles. Nevertheless, residual effects of these risk factors and of other covariates cannot be ruled out.

In particular, we found a correlation between the environmental waste risk indicator (MRI) and breast cancer mortality in women and hospitalization in both genders. The occurrence of male breast cancer is a very rare event. Breast cancer is associated with sufficient evidence with exposure to alcoholic beverages, estrogen–progesterone therapies and diethylstilbestrol, x-rays, and gamma radiation; limited evidence has been found for the association with dioxins, tobacco smoking, estrogen menopausal therapy, shift work, and exposure to PCBs (56). In addition, the excess of testicular cancer in hospitalization analysis recognizes some of the same risk factors as breast cancer, such as exposure to endocrine disruptor chemicals (EDCs: heavy metals, POPs) (57, 58). Previous biomonitoring studies performed in the



same territory reported high levels of POPs and heavy metals in subareas with hazardous waste sites (51–54). The evidence of the association of breast and testis cancers with exposure to hazardous waste sites was defined as limited by the systematic review published in 2017 (8).

The hospitalization risk from asthma was significantly higher in the highest MRI classes (classes three and four). An increase in asthma was reported in the population living in the atmospheric pollutant areas. The emission of airborne pollutants by waste sites was documented (59, 60), and an increase in asthma and respiratory diseases were related to the residence near hazardous waste sites (60); in addition, in the study area, waste burning acts were largely documented.

Particular attention has to be paid to the increased risks in pediatric–adolescent subpopulations. As compared to adults, in fact, children, in general, experience higher exposure to environmental agents due to their activity patterns, behavior and physiological characteristics, and immaturity of organs and systems (<https://www.epa.gov/children>). Moreover, children spend more time outdoors and have higher respiratory rates. They also play close to the ground, potentially increasing their contact with

polluted soils (61, 62). At the same time, children neither are usually exposed to many lifestyle factors like adults nor do they experience occupational exposures, at least in most high-income countries, such as Italy. Therefore, a stronger effect and fewer confounders are expected in children living in our study area compared to the adult population, making the detected exceeding risk as “sentinel events” to be further attentioned. This is the case of the observed increase of hospitalization for leukemia, asthma, and acute respiratory diseases in the MRI classes most impacted by waste, which supports the hypothesis of possible environmental exposure to air pollutants among children. In particular, hospitalization from leukemias is in excess in all MRI classes most impacted by the waste sites. An increase in hematological diseases were related to the residence of hazardous waste sites containing benzene (59), and childhood leukemia has been found to be associated with residential proximity to industrial plants involved in the hazardous waste sector (63).

The high risk of prevalence of preterm birth (PTB), observed in all MRI classes, with respect to MRI class 1, was related to the mother’s environmental exposure to waste sites in the gestational period (10), and the evidence of the association was limited



FIGURE 6  
Some illegal waste dumping and burning sites in the study area.

(8). Socio-demographic factors, such as ethnicity, older age, low education levels, and smoking of the mothers, were also reported as risk factors for PTB (64). The excess of PTB is of particular interest, considering that it could represent a risk for disorders and health outcomes in adult life. PTB is a major cause of death since complications arising from these adverse reproductive outcomes are the single largest direct cause of neonatal deaths, and after pneumonia, it is the second most common cause of children under-5 years deaths (65). Effects of preterm birth on a long-term scale are documented in some reviews showing a significantly increased risk for altered cardiovascular and renal functions in young adulthood (66), higher blood pressure (67, 68), and several components of the metabolic syndrome and cardiovascular disease in adult life (69).

To correctly understand the meaning of the present study, it can be helpful to examine a few points, also bearing in mind the abovementioned limitations.

The last two decades have witnessed a growing interest in the international scientific community and of the WHO (specifically of the WHO Regional Office for Europe) in the health impact of inappropriate, if not openly illegal, methods of waste management. The most important event in this frame has been the inclusion of the topic “Waste disposal, management and trafficking and contaminated sites” among the priorities of the Declaration of the Sixth Ministerial Conference on Environment and Health of the European Region of the WHO held in Ostrava (Czech Republic) on 13–15 June 2017 (7). The inclusion of the notion of waste trafficking

clearly shows the underlying relevance of the criminal world in this domain. In contrast, this phenomenon implies a strong synergy between health and judicial authorities.

In this context, one pivotal issue is to estimate the health impact of illegal waste disposal procedures. This is a most critical question because it is well-known that epidemiological studies of environmental factors produce valuable findings in terms of public health because they encompass valid procedures for exposure assessment. In this domain, though, exposure assessment is difficult because, by definition, the criminal organizations work in secret and hide as much as possible the location of the dumping sites (in addition, obviously, their specific chemical contamination). Epidemiology, being an observational, non-experimental discipline, requires the adoption of highly validated protocols to concur to the detection of causal webs between environmental exposures and health impacts [for an overview of these items, among others (47), refer to (70–73)].

When epidemiological issues are brought in the Courts, the complexity of causal evaluations increases, especially because the object of epidemiology is population health, while the issues of both toxic tort litigations and criminal prosecution concern the health of specific individuals, plaintiffs, or ascertained victims [see, among else, (74–78) references]. With respect to causal links that are well-assessed in scientific terms, such as the inhalation of asbestos fibers and the occurrence of pleural mesothelioma, doubts about biological mechanisms of action can lead to unexpected absolutions, as discussed by the Italian Association of Epidemiology in a recent position article (79).

In light of the abovementioned evidence, the purpose of the present study consists in to confirm or refute the hypothesis of a correlation between the GIS-based indicator of waste risk and the occurrence of excess cases of different diseases aggregated at the municipality level. This observation may be helpful for setting priorities for environmental cleanup with particular care for areas where indicators of children and adolescents' health are more critical.

The current limitations in our knowledge may impair the search for sufficient evidence of an association between exposure to complex chemical cocktails of pollutant agents and a wide range of adverse health outcomes. The same limitations, however, do not impede us from using the findings of the present study to guide appropriate policies on the study territory and, given the consistency of the results reported in the literature, in similar contexts. Special attention should be given to the most vulnerable population subgroups in the frame of a precautionary approach.

To reduce environmental exposure, through the contrast of illegal waste mismanagement and trafficking, the implementation of environmental remedial actions and of safe waste management is among the priority prevention acts recommended by the WHO (7). The implementation of a circular economy, with the reduction of waste production and the increase of waste reuse and recycling, seems particularly urgent at both the local and global levels.

Based on recent estimates (2020 <https://www.isprambiente.gov.it/it/publicazioni/rapporti/rapporto-rifiuti-urbani-edizione-2021>), in the Campania Region, the separate collection of waste concerns 54% of the urban waste (~2.5 million tons); in Naples and Caserta provinces (that include the study area), the percentage

is similar: 48 and 54%, respectively. Moreover, about 50,000 tons of urban waste are managed in landfills outside the region, and 1% in regional landfills. In terms of hazardous waste, ~8 million tons are produced at the regional level, with 75% being recovered and the remaining 25% being heat treated. Nevertheless, uncontrolled and illegal waste dumping and burning of both urban and hazardous waste continue to occur.

These actions require measures by judiciary authorities, in terms of repression, and by administrative authorities, in terms of prevention (80). The international trade of waste, in particular of hazardous waste from industrialized to low-middle income countries (LMCIs) requires global efforts to contrast illegal acts and to control the respect of International Agreements, such as the “Basel Convention on the Control of Transboundary movements of hazardous waste and their management” and the related regulations. These efforts, at the global level, are particularly compelling, also in light of the more recent articles on the population living near waste sites and the informal workers in waste management, often children and women, in LMCIs.

In addition, healthcare and assistance plans should be implemented in these areas, with special attention paid to maternal and pediatric health and oncological diseases. The achievement of health assistance and prevention acts is strongly related to the participation of the local communities and communication plans involving public institutions and stakeholders (81).

The complexity of these contexts requires collaboration, at the global and local levels, between all institutions and organizations, including non-governmental organizations (NGOs) and citizen committees (80).

Notwithstanding the need to implement the abovementioned acts, further additional research on this issue could increase our knowledge to better point out the more appropriate actions. The majority of the published articles concern ecological studies, such as the present, and often this study design is the only possible choice, considering the huge impacted areas (80). The limitations of these studies, in order to test hypotheses of the association disease/risk factor, have been mentioned earlier. Epidemiological investigations at the individual level and human biomonitoring studies could provide useful information on the exposure and the possible biological mechanisms. The mixture of chemicals present in these sites, often unknown, make critical the development and the informativeness of these studies (80). In this regard, some articles have addressed the complexity in assessing exposure and impact of waste of industrial origin, with particular attention to the innovative exposome approach in relation to multi-route and multi-pathway exposure (82–84). In addition, some health outcomes, recently highlighted in people exposed to hazardous waste, such as diabetes, neurological and cognitive development, and physical growth, deserve further particular attention and specific focus.

Finally, the present study represents a particular example of a collaborative approach between institutions with different, though complementary, mandates: a national public health institute, in charge of identifying the health effects of exposure to environmental risk factors to identify idoneous primary preventive actions, including environmental remediation; a Prosecution

Office with a specific mission to contrast and prosecute illegal waste trafficking and mismanagement in areas with documented hazardous waste contamination. The combination of the two approaches appears to be of particular interest, considering the large worldwide diffusion of illegal waste practices and transboundary trade, concerning, in particular, LMICs. The adopted investigation procedure and epidemiological methods, notwithstanding the abovementioned limitations, could represent a useful approach to deal with areas highly contaminated by an unknown mixture of toxic contaminants from several point sources.

## Conclusion

A correlation between illegal waste sites and specific diseases was observed in an area highly affected by waste sites. In particular, mortality from breast cancer in women and hospitalization from testis cancer were found to be correlated with the environmental municipal waste risk index. The hospitalization from breast cancer and asthma exceeded in both genders in the municipalities most impacted by waste sites. Among 0–19-year-old people, a positive correlation with the risk index was found for hospitalization from leukemias and for the prevalence of preterm birth.

The present results confirm that waste mismanagement, in particular of hazardous waste, could represent a health risk for the population. The implementation of policies for environmental remediation of the sites, the contrast of illegal and unsafe waste management and trafficking, and the implementation of a virtuous waste circular economy are warranted at the local and global levels.

## Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: the analysis of the data used in this study complies with the European General Data Protection Regulation (EU GDPR 2016/679) which authorized the processing of personal data relating to hospital discharge forms and causes of death by ISS and other public institutions for reasons of public interest in public health. Written consent for participation was not required for this study, in accordance with national legislation and institutional requirements. Requests to access these datasets should be directed to GM, [giada.minelli@iss.it](mailto:giada.minelli@iss.it).

## Ethics statement

Ethical review and approval was not required for the study of human participants in accordance with the local legislation

and institutional requirements. Written informed consent from the patients/participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

## Author contributions

LF, PC, and II were involved in the conception and design of the study and in data interpretation. LF was involved in writing the original draft preparation, review, and revision of the manuscript. PC and II were involved in reviewing the manuscript. VM and GM were involved in data collection, data analysis, and manuscript review. EB, FS, and MD were involved in data collection and manuscript review. EM was involved in writing the original draft preparation and reviewed the manuscript. DA was involved in the conception of the study and reviewed the manuscript. All authors have read and agreed to the final manuscript.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fpubh.2023.996960/full#supplementary-material>

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# Occupational Exposure to Mercury at an Electronics Waste and Lamp Recycling Facility — Ohio, 2023

Dallas S. Shi, MD, PhD<sup>1,2</sup>; Melissa Charles, MS<sup>1</sup>; Catherine Beaucham, PhD<sup>1</sup>; Sheldon Walker<sup>1</sup>; Walter Alarcon, MD<sup>1</sup>; Scott E. Brueck, MS<sup>1</sup>; Sophia K. Chiu, MD<sup>1</sup>; Nicholas Somerville, MD<sup>1</sup>

## Abstract

Workers in electronics waste and lamp recycling facilities are at risk of exposure to elemental mercury through inhalation of mercury vapor and mercury-containing dust. Employers at an electronics waste and lamp recycling facility in Ohio that crushes mercury-containing lamps expressed concerns about mercury exposure from work processes and requested a health hazard evaluation by CDC's National Institute for Occupational Safety and Health (NIOSH). In April 2023, NIOSH conducted a multidisciplinary investigation to assess elemental and inorganic mercury exposures, including epidemiologic, environmental, and ventilation assessments. Results indicated that mercury vapor was detected throughout the facility, with six of 14 workers having elevated urine mercury levels. These workers had a median job tenure of 8 months; four did not speak English, and five reported symptoms consistent with mercury toxicity, such as metallic or bitter taste, difficulty thinking, and changes in personality. Recommendations included improving the ventilation system, changing work practices to reduce mercury exposure, and providing training and communication tailored to the worker. As the electronic waste recycling industry continues to grow, it is important for employers to evaluate mercury exposure and safeguard employees using a hierarchy of controls. Health departments should consider monitoring occupational mercury exposure in recycling facilities, and clinicians should be aware of the potential for mercury toxicity among workers in these settings.

## Investigation and Results

Mercury exposure is an occupational hazard with serious health consequences, including neurological symptoms such as tremors, memory loss, and difficulty concentrating, as well as kidney damage and other systemic effects (*1*). Elemental mercury exposure occurs primarily through inhalation of mercury vapor, which can be rapidly absorbed into the bloodstream. Chronic exposure, even at low levels, can lead to cumulative health effects over time (*1,2*).

Occupational limits have been established to safeguard workers against mercury exposure. These limits include the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) of 25  $\mu\text{g}/\text{m}^3$ , the National Institute for Occupational Safety and Health's

(NIOSH) recommended exposure limit (REL) of 50  $\mu\text{g}/\text{m}^3$ , and the Occupational Safety and Health Administration's (OSHA's) permissible exposure limit (PEL) of 100  $\mu\text{g}/\text{m}^3$ . ACGIH TLV and NIOSH REL are recommended exposure limits to prevent adverse health effects among workers; OSHA PEL is a legally enforceable limit.

Workers in electronics waste and lamp recycling facilities face unique risks for mercury exposure due to the crushing and processing of mercury-containing lamps (*3*). Mercury vapor and dust can become airborne, creating significant inhalation risks. In response to concerns raised by employers at an electronics waste and lamp recycling facility in Ohio about mercury exposure from work processes, NIOSH conducted a health hazard evaluation (HHE).<sup>\*</sup> The evaluation, carried out in April 2023, involved a multidisciplinary team of industrial hygienists, epidemiologists, and medical officers. During a 2-day site visit, CDC investigators conducted a cross-sectional epidemiologic study by interviewing 15 workers, performed environmental sampling for mercury vapor, assessed the facility's ventilation system to identify potential sources and levels of mercury exposure, and offered spot urine testing (*4*). This activity was reviewed by CDC, deemed not research, and conducted consistent with applicable federal law and CDC policy.<sup>†</sup>

## Facility and Work Process Description

The facility was a two-story warehouse divided into four sections: 1) administrative areas; 2) common spaces (entrance, hallways, bathrooms, breakroom, conference room, locker room, and personal protective equipment [PPE] storage); 3) lamp recycling areas (lamp room, glass roll-off, shaker, and retort furnace); and 4) additional workspaces (material storage, battery and ballast sorting, and bulb storage). During an 8-hour work day, lamp room workers load mercury-containing bulbs onto a conveyor for crushing. A sorting machine divides the bulbs into glass (deposited in the glass roll-off area), metal, and mercury dust (further sieved into ultrafine dust by the shaker). The retort furnace, which extracts mercury from ultrafine dust using heat, was not in use at the time of HHE. Workers in the battery and ballast areas prepare electrode components, such

<sup>\*</sup> <https://www.cdc.gov/niosh/hhe/default.html>

<sup>†</sup> 45 C.F.R. part 46.102(l)(2), 21 C.F.R. part 56; 42 U.S.C. Sect. 241(d); 5 U.S.C. Sect. 552a; 44 U.S.C. Sect. 3501 et seq.

as metal or graphite parts, for shipment to facilities where they are reused or recycled into new batteries or other products. Employees in the lamp room and retort furnace area wear half-mask elastomeric respirators (reusable respirators made from a flexible material that provides a tight seal and are equipped with replaceable cartridges for filtering mercury vapor), steel-toed boots, safety glasses, and a company-issued long-sleeved shirt.

### Worker Interviews and Spot Urine Testing

All 15 workers at the facility participated in a semistructured interview about employment history, work characteristics, signs and symptoms consistent with mercury toxicity, and medical and social histories. Workers were given the option to undergo spot urine testing for inorganic and elemental mercury at the time of the interview. Spot urine testing was chosen because of its convenience, instead of 24-hour urine or end-of-shift collection at the end of the workweek. Urine specimens were analyzed by Associated Regional and University Pathologists, Inc. (<https://www.aruplab.com/>) laboratories using inductively coupled plasma mass spectrometry, an analytic technique that can detect the concentration of elements and their isotopes in a sample. Creatinine levels, a marker of kidney function, were measured, and urine mercury-to-creatinine ratios were calculated for comparison with the ACGIH Biologic Exposure Index (BEI) of 20.0  $\mu\text{g/g}$  creatinine. BEI is a guideline value indicating the level of a substance in biologic samples below which most workers are unlikely to experience adverse health effects.

### Environmental and Personal Air Sampling Methodology

Direct area air sampling for elemental mercury vapor was conducted during 2 work days using a Jerome J405 atomic fluorescence mercury vapor analyzer ([https://www.pine-environmental.com/products/jerome\\_j405](https://www.pine-environmental.com/products/jerome_j405)). A total of 171 direct area air samples were measured at breathing height (approximately 5 ft [1.5 m] above floor level) to assess mercury vapor levels across the facility. Comparisons to occupational exposure limits were used to identify potential areas of concern within the facility. In addition, all workers were offered the opportunity to participate in personal air sampling, which involved collection of full-shift personal breathing zone samples for mercury vapor analysis during 2 days to directly compare against occupational exposure limits.

### PPE Use

Inconsistent use of recommended PPE was observed throughout the facility. Observations during the site visit revealed that, particularly in the lamp room where respirators

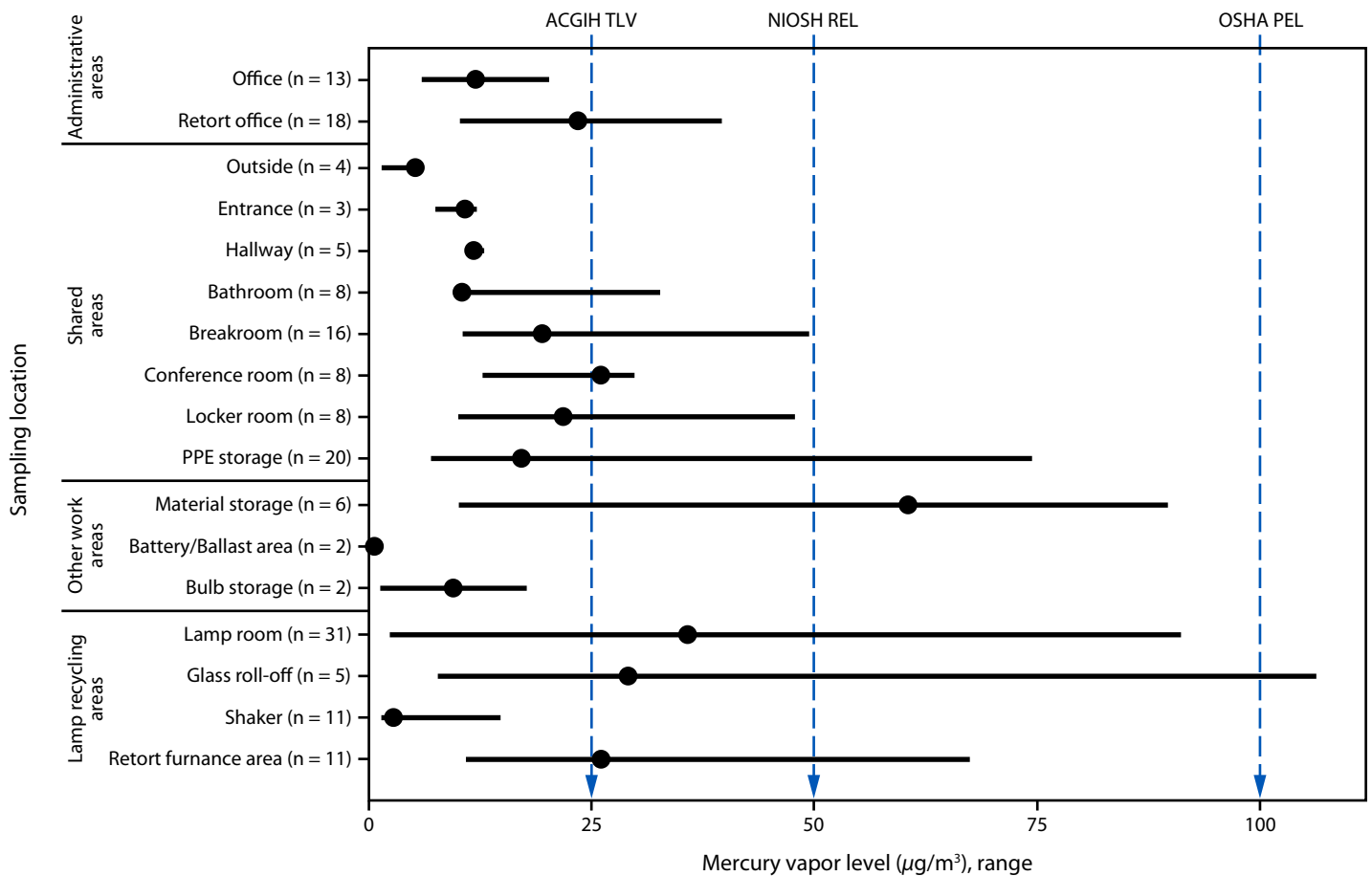
are mandatory, workers frequently did not adhere to proper PPE use. Instances included employees removing their respirators or wearing them incorrectly, such as one employee using an N95 respirator with one of the straps cut off, severely compromising the respirator's seal. Other observations included sporadic use of gloves and protective clothing. These observations were further corroborated by worker interviews. Some workers reported challenges with the fit and comfort of their PPE, while others cited a lack of understanding regarding the proper use and maintenance of equipment. Language barriers among workers appeared to exacerbate these issues, as training and communication were not always provided in workers' preferred languages.

### Environmental Air Sampling Findings

Mercury was detected in all 171 direct area air samples (Figure). In areas outside of the lamp recycling areas (lamp room, glass roll-off, shaker, and retort areas), referred to as nonproduction areas, the median mercury vapor concentrations in the conference room (26.0  $\mu\text{g}/\text{m}^3$ ; range = 12.8–29.8  $\mu\text{g}/\text{m}^3$ ) and material storage area (60.5  $\mu\text{g}/\text{m}^3$ ; range = 10.1–89.7  $\mu\text{g}/\text{m}^3$ ) exceeded the ACGIH TLV of 25  $\mu\text{g}/\text{m}^3$ . The median mercury vapor concentration in the material storage area also exceeded the NIOSH REL of 50  $\mu\text{g}/\text{m}^3$ . In production areas, the median mercury vapor concentrations in the lamp room (35.8  $\mu\text{g}/\text{m}^3$ ; range = 2.5–91.1  $\mu\text{g}/\text{m}^3$ ), glass roll-off area (29.1  $\mu\text{g}/\text{m}^3$ ; range = 7.8–106.3  $\mu\text{g}/\text{m}^3$ ), and retort furnace area (26.1  $\mu\text{g}/\text{m}^3$ ; range = 10.9–67.5  $\mu\text{g}/\text{m}^3$ ) were also above ACGIH TLV. One sample from the glass roll-off area (106.3  $\mu\text{g}/\text{m}^3$ ) exceeded both NIOSH REL and OSHA PEL.

### Results of Urine Testing and Personal Air Sampling

All 15 employees participated in urine collection. One urine sample was too diluted to interpret. Among six workers in the lamp recycling area, the median mercury-to-creatinine ratio was 41.3  $\mu\text{g/g}$ , and the levels of five of these workers exceeded ACGIH BEI (Table 1). Among three workers in administrative areas and five in other work areas, the median urine mercury-to-creatinine ratios were 8.6  $\mu\text{g/g}$  and 5.8  $\mu\text{g/g}$ , respectively. Overall, six of 14 workers had spot urine mercury levels above ACGIH BEI, including five of six workers in the lamp recycling areas and one of five workers in other work areas. All six workers in the lamp recycling areas and three of those in other work areas participated in personal air sampling. Five of six workers in the lamp recycling areas had personal air exposures to mercury vapor above the ACGIH TLV of 25  $\mu\text{g}/\text{m}^3$  (median = 64.8  $\mu\text{g}/\text{m}^3$ ).

**FIGURE. Median mercury vapor levels, by work location at an electronic waste and lamp recycling facility — Ohio, 2023**

**Abbreviations:** ACGIH = American Conference of Governmental Industrial Hygienists; NIOSH = National Institute for Occupational Safety and Health; OSHA = Occupational Safety and Health Administration; PEL = permissible exposure limit; PPE = personal protective equipment; REL = recommended exposure limit; TLV = threshold limit value.

**TABLE 1. Median spot urine mercury levels and personal mercury vapor exposure levels among workers at an electronic waste and lamp recycling facility, by primary work location (N = 15) — Ohio, 2023**

| Primary job location | No. of workers | Median (range) urine mercury to creatinine ratio (µg/g) | No. (%) of samples >ACGIH BEI* | No. of personal air samples | Median (range) personal mercury vapor exposure (µg/m³) <sup>†</sup> | No. (%) of samples >ACGIH TLV <sup>§</sup> |
|----------------------|----------------|---------------------------------------------------------|--------------------------------|-----------------------------|---------------------------------------------------------------------|--------------------------------------------|
| Lamp recycling areas | 6              | 41.3 (16.1–64.0)                                        | 5 (83)                         | 12                          | 64.8 (10.7–81.8)                                                    | 10 (83)                                    |
| Administrative areas | 3              | 8.6 (4.2–13.0)                                          | 0 (—)                          | 0                           | —                                                                   | —                                          |
| Other work areas     | 5 <sup>¶</sup> | 5.8 (1.3–45.2)                                          | 1 (20)                         | 6                           | 6.6 (2.9–11.5)                                                      | 0 (—)                                      |
| <b>Total</b>         | <b>14**</b>    | <b>51.0 (1.3–64.0)</b>                                  | <b>6 (43)</b>                  | <b>18</b>                   | <b>33.6 (2.9–81.8)</b>                                              | <b>10 (56)</b>                             |

**Abbreviations:** ACGIH = American Conference of Governmental Industrial Hygienists; BEI = biologic exposure index; TLV = threshold limit value.

\* ACGIH BEI for inorganic mercury in urine is 20 µg/g creatinine.

<sup>†</sup> Personal air sampling was collected over the course of two shifts per worker. In total, nine workers participated with a total of 18 samples collected. Workers in the administrative areas did not participate in personal air sampling.

<sup>§</sup> ACGIH TLV for elemental mercury is 25 µg/m³.

<sup>¶</sup> All five workers participated in urine testing; three participated in personal air sampling.

\*\* Urine specimen from one employee was too diluted to interpret.

## Characteristics of Workers with Elevated Spot Urine Mercury Levels

Of the 14 workers whose spot urine samples were sufficiently concentrated for interpretation of mercury levels, six had levels exceeding ACGIH BEI (Table 2). Among these, all were male and four were Spanish-speaking. All eight workers with mercury levels below BEI primarily spoke English and worked in production areas. Median job tenure of workers with mercury levels above BEI was 8 months compared with 23 months among workers with mercury levels below BEI. Five of the six workers with levels above BEI reported signs and symptoms consistent with mercury exposure, including a metallic or bitter taste, difficulty thinking, or personality changes (three each); difficulty writing or loss of balance, light headedness, or dizziness (two each); and skin rash, headache, numbness or tingling in hands or feet, weight loss, or diarrhea (one each). (Participants could identify any signs or symptoms that began after their employment began at the recycling facility, and multiple signs and symptoms could be reported by each participant.) Four of the eight workers with levels below BEI reported no symptoms.

## Public Health Response

Recommendations to protect workers based on a hierarchy of controls<sup>§</sup> approach were provided to the facility (4). Recommended engineering controls included installing local exhaust ventilation over the conveyor in the lamp room and maintenance of the facility's heating, ventilation, and air conditioning systems. Other recommendations included implementing a workflow progressing from clean to dirty zones to prevent the spread of mercury to clean areas, improving housekeeping, tailoring training in workers' preferred languages, and standardizing use of recommended PPE.

## Discussion

The expansion of the recycling industry offers opportunities to promote sustainable waste management practices but also raises challenges related to workers' health (5). This investigation highlights occupational health concerns at an electronics waste and lamp recycling facility, where identification of environmental mercury vapor and individual worker urine mercury concentrations surpassing ACGIH safety thresholds indicate a need for enhanced protective measures and monitoring. Previous studies have consistently demonstrated the occupational hazards posed by mercury exposure in recycling

**TABLE 2. Demographic characteristics and symptoms of electronic waste and lamp recycling facility workers with spot urine mercury levels above and below the American Conference of Governmental Industrial Hygienists biologic exposure index\* (N = 14) — Ohio, 2023**

| Characteristic                                      | No. (%), by urine mercury level |                     |
|-----------------------------------------------------|---------------------------------|---------------------|
|                                                     | ≤20 µg/g creatinine             | >20 µg/g creatinine |
| <b>No. of workers</b>                               | 8                               | 6                   |
| <b>Median age, yrs (range)</b>                      | 40 (25–53)                      | 41 (35–54)          |
| <b>Sex</b>                                          |                                 |                     |
| Female                                              | 2 (25)                          | 0 (—)               |
| Male                                                | 6 (75)                          | 6 (100)             |
| <b>Primary language</b>                             |                                 |                     |
| English                                             | 8 (100)                         | 2 (33)              |
| Spanish                                             | 0 (—)                           | 4 (67)              |
| <b>Job tenure, mos, median (range)</b>              | 23 (14–144)                     | 8 (3–32)            |
| <b>Self-reported signs and symptoms<sup>†</sup></b> |                                 |                     |
| Any sign or symptom                                 | 4 (50)                          | 5 (83)              |
| Metallic or bitter taste                            | 1 (13)                          | 3 (50)              |
| Difficulty thinking                                 | 0 (—)                           | 3 (50)              |
| Changes in personality                              | 0 (—)                           | 3 (50)              |
| Difficulty writing                                  | 0 (—)                           | 2 (33)              |
| Loss of balance, lightheadedness, or dizziness      | 0 (—)                           | 2 (33)              |
| Skin rash or sore                                   | 1 (13)                          | 1 (17)              |
| Headaches                                           | 3 (38)                          | 1 (17)              |
| Numbness or tingling in hands or feet               | 1 (13)                          | 1 (17)              |
| Unplanned weight loss                               | 1 (13)                          | 1 (17)              |
| Diarrhea                                            | 1 (13)                          | 1 (17)              |
| No reported sign or symptom                         | 4 (50)                          | 1 (17)              |

\* 20 µg/g creatinine.

<sup>†</sup> Reported signs and symptoms are not mutually exclusive. Participants could identify any symptoms that began after their employment began at the recycling facility, and multiple symptoms could be reported by each participant.

and manufacturing settings, and underscore the importance of comprehensive safety protocols that help worksites adhere to recommended exposure limits (3,6). Observed inconsistent proper PPE use likely contributed to high urine mercury measurements despite the use of respiratory protection, indicating a need for enforcement of safety protocols and targeted training to support proper PPE use.

Elevated mercury vapor levels were also identified in areas of the facility not directly involved in lamp recycling. Although personal exposure measurements for mercury in these areas did not surpass ACGIH TLV, one worker with no direct involvement in lamp recycling had elevated urine mercury levels. This finding suggests that contamination of nonproduction areas can affect nonproduction workers. Mercury exposure below established occupational limits can have harmful health effects over time, including neurologic symptoms such as tremors, memory problems, and difficulty concentrating, as well as kidney damage (1,2). To mitigate these risks, comprehensive controls are essential. The diverse nature of recycling operations means that workers, regardless of their direct involvement with recycling processes, might be exposed to hazardous substances such as mercury.

<sup>§</sup> The hierarchy of controls is a framework that groups corrective actions by their likely effectiveness in reducing or removing hazards from the workplace. Levels in the hierarchy include elimination, substitution, engineering controls, administrative or work-practice controls, and PPE. <https://www.cdc.gov/niosh/hierarchy-of-controls/about/index.html>

## Summary

### What is already known about this topic?

Workers in electronics waste and lamp recycling facilities face health risks from inhaling mercury vapor and mercury-containing dust.

### What is added by this report?

At an Ohio electronics waste and lamp recycling facility, mercury vapor was found throughout, and six of 14 workers had elevated urine mercury levels. Among those with elevated urine mercury, the median job tenure was 8 months; four workers did not speak English, and five reported signs and symptoms consistent with mercury toxicity.

### What are the implications for public health practice?

Employers at electronics waste and lamp recycling facilities are encouraged to evaluate mercury exposure and implement controls such as enhancing ventilation systems and providing training tailored to the worker.

This investigation identified a disparity in exposure levels among workers with different primary languages and job tenure, suggesting potential barriers to effective communication and training (2,7). These findings align with broader occupational health literature, which identifies language barriers and job tenure as factors influencing health and safety (7–9). The higher prevalence of self-reported symptoms among workers with elevated mercury levels reinforces the need for ongoing health monitoring to mitigate the adverse health effects of mercury.

Employers at recycling facilities can implement comprehensive exposure mitigation strategies that align with the hierarchy of controls. These strategies include enclosing spaces with the highest potential for mercury exposure to prevent contamination of nonproduction areas, improved ventilation, use of appropriate PPE, regular exposure surveillance, and training programs tailored to worker needs. Health departments with recycling facilities in their jurisdiction should be aware of the potential for mercury exposure, while clinicians should remain vigilant for signs and symptoms of mercury toxicity among workers in these environments. Regular monitoring is essential to ensure that controls are effective and to detect any changes in exposure levels (10).

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Corresponding author: Dallas S. Shi; Dshi@cdc.gov.

<sup>1</sup>Division of Field Studies and Engineering, National Institute for Occupational Safety and Health, CDC; <sup>2</sup>Epidemic Intelligence Service, CDC.

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## Notes from the Field

### Elevated Atmospheric Lead Levels During the Los Angeles Urban Fires — California, January 2025

Haroula D. Baliaka<sup>1</sup>; Ryan X. Ward<sup>1</sup>; Roya Bahreini<sup>2</sup>;  
Ann M. Dillner<sup>3</sup>; Armistead G. Russell<sup>4</sup>; John H. Seinfeld<sup>1</sup>;  
Richard C. Flagan<sup>1</sup>; Paul O. Wennberg<sup>1</sup>; Nga L. Ng<sup>4</sup>

On January 7, 2025, the Eaton Canyon and Palisades fires blazed across the Los Angeles region, driven by exceptionally dry conditions and Santa Ana wind gusts approaching 100 mph (161 kph). The fires spread rapidly into densely populated neighborhoods along the wildland-urban interface, destroying approximately 16,000 structures. As of February 10, 2025, a total of 29 deaths had been identified.\* In addition to the deaths and destruction of property, wildfires emit a complex mixture of air pollutants and contribute to elevated concentrations of fine particulate matter (PM<sub>2.5</sub>; particulate matter with a diameter <2.5  $\mu\text{m}$ ), degrading air quality many miles downwind. Exposure to wildfire PM<sub>2.5</sub> has been linked to adverse health effects including increased asthma cases, respiratory symptoms, aggravated respiratory diseases, and increased overall mortality (1–3). Unlike conventional wildfires that primarily burn natural fuels (e.g., grasslands or forests), the Eaton Canyon and Palisades fires ignited significant portions of the built environment, in which painted surfaces, pipes, vehicles, plastics, electronic equipment, and the structures themselves became the fuel. This widespread combustion of synthetic materials has increased concerns about the toxicity of PM<sub>2.5</sub>, because a large proportion of the structures affected by the fires were built before 1978, when use of leaded paint was still common. This report focused on measuring airborne PM<sub>2.5</sub> lead during the Los Angeles urban fires.

#### Investigation and Outcomes

The Atmospheric Science and Chemistry Measurement Network (ASCENT)<sup>†</sup> is a new, nationwide, multi-institutional initiative funded by the National Science Foundation, to provide continuous measurements of PM<sub>2.5</sub> chemical components (organics, inorganics, metals, and black carbon) across 12 sites in the United States, including seven urban and five remote or rural areas.<sup>§</sup> All ASCENT sites were operating and sampling ambient air as of May 2024.

\* <https://www.fire.ca.gov/incidents/> (Accessed February 10, 2025).

<sup>†</sup> <https://ascent.research.gatech.edu/>

<sup>§</sup> The seven urban areas are Atlanta, Georgia; Denver, Colorado; Houston, Texas; Los Angeles, California; New York, New York; Pittsburgh, Pennsylvania, and Riverside, California. The five remote or rural areas include Alaska, Cheeka Peak/Makah in Washington, and the Great Smoky Mountains, Joshua Tree, and Yellowstone National Parks.

The Los Angeles ASCENT site in Pico Rivera, approximately 14 miles (23 kilometers) south of the Eaton Canyon fire, has been operating since July 2023. During and immediately after the Los Angeles fires, southward winds transported the fire plume to the ASCENT site. Hourly PM<sub>2.5</sub> lead measurements recorded during and after the fires were reviewed to assess their contribution to atmospheric lead levels. Because this analysis consists of a review of routinely collected environmental data and does not include human subjects, human subjects review was not required by the authors' institutions.

During January 2–6, 2025, the average PM<sub>2.5</sub> lead concentration recorded at the Los Angeles ASCENT site was 0.00068  $\mu\text{g}/\text{m}^3$ . From January 8 to January 11, PM<sub>2.5</sub> lead concentration increased approximately 110 times with an average concentration of 0.077  $\mu\text{g}/\text{m}^3$  (Figure). Recorded PM<sub>2.5</sub> lead concentration peaked at approximately 0.5  $\mu\text{g}/\text{m}^3$  on January 9. By the evening of January 11, PM<sub>2.5</sub> lead concentration had returned to levels similar to those before the fire. The presence of heavy metals such as lead is not unusual in urban fire emissions, particularly in California, where legacy pollutants from older infrastructure, industrial sources, and soils can be remobilized during fires (2,4). For example, during the 2018 Camp fire, monitors recorded ambient PM<sub>2.5</sub> lead concentrations that averaged 0.13  $\mu\text{g}/\text{m}^3$  during a period of 17 hours (2).

Few data illustrate the health effects of lead from inhalation compared with other exposure routes. The ASCENT real-time measurements of airborne lead and other chemical constituents in PM<sub>2.5</sub> provide valuable PM<sub>2.5</sub> chemical composition data that can be combined with health data to examine health effects of individual smoke components from the Los Angeles fires.

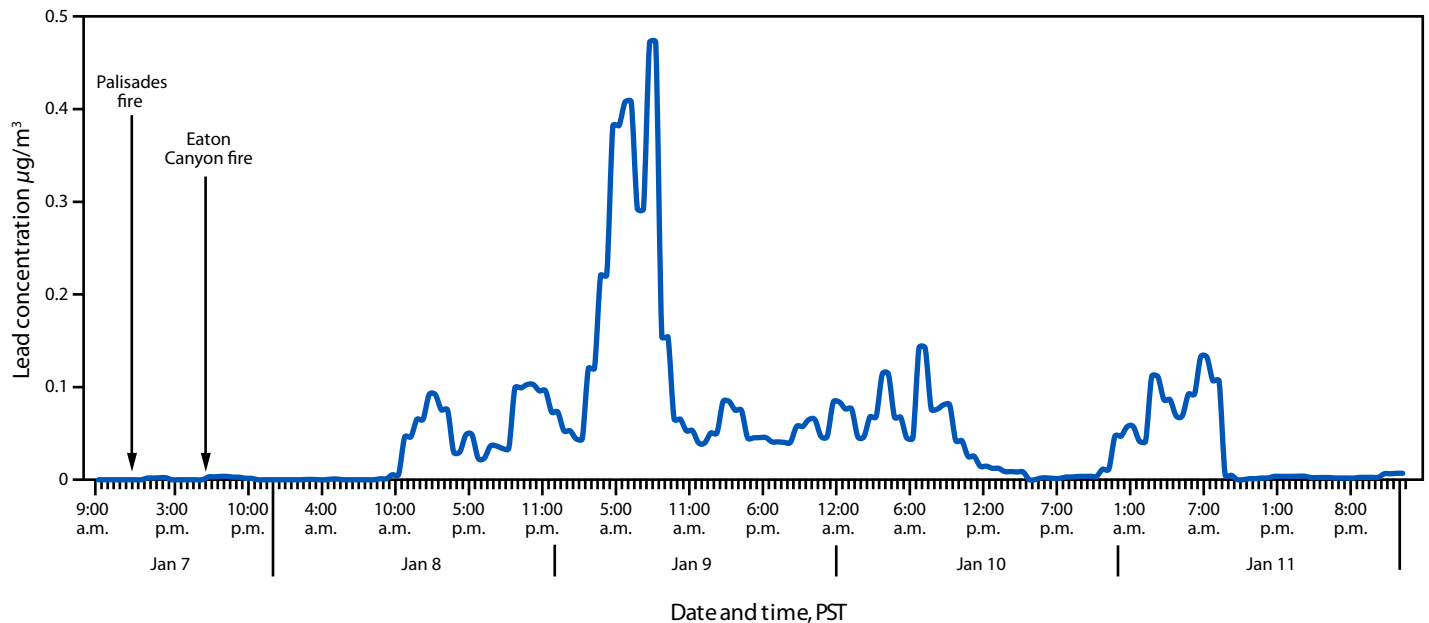
#### Preliminary Conclusions and Actions

Lead is a toxic air contaminant that is distributed in multiple human tissues and accumulates in teeth and bones; it affects nearly every organ system, posing significant health risks, particularly for children, who are more vulnerable to its neurodevelopmental effects (2,3,5). Regulatory efforts, especially the U.S. Clean Air Act of 1970, have resulted in a sharp decline in airborne lead levels during the past 45 years.<sup>¶</sup> The current National Ambient Air Quality Standard for lead in total suspended particles over a 3-month rolling average is 0.15  $\mu\text{g}/\text{m}^3$ .<sup>\*\*</sup> Measures including removing lead from gasoline

<sup>¶</sup> <https://www.epa.gov/laws-regulations/summary-clean-air-act>

<sup>\*\*</sup> <https://www.epa.gov/lead-air-pollution/national-ambient-air-quality-standards-naaqs-lead-pb>

**FIGURE.** Hourly lead concentrations<sup>\*,†</sup> of particulate matter <2.5  $\mu\text{m}$  in diameter at the Los Angeles Atmospheric Science and Chemistry mEasurement NeTwork site relative to the start of the Palisades and Eaton Canyon fires — Pico Rivera, California, January 7–12, 2025



\*  $\mu\text{g}/\text{m}^3$ .

† The National Ambient Air Quality Standard for lead in total suspended particles over a 3-month rolling average is 0.15  $\mu\text{g}/\text{m}^3$ .

and leaded pipes and the banning or limiting of lead in consumer products, such as residential paint, have led to a 97% decrease in airborne lead concentrations in the United States since 1980 (5). However, unlike chronic lead exposure, which has been widely studied, the health effects of brief, elevated lead exposures, such as those described in this report, are not well understood. Additional health research is needed, because airborne lead levels alone do not necessarily indicate exposure.

PM<sub>2.5</sub> is not a single entity but comprises a complex mixture of chemical components with dynamic size distributions, temporal and spatial variations, and toxicity. Whereas the health effects of PM<sub>2.5</sub> exposure are well documented, studies assessing which sources, chemical compounds, and sizes of particles contribute to health effects are lacking. ASCENT fills in this gap by providing high time-resolution and chemical composition measurements of PM<sub>2.5</sub> across dynamic size ranges with advanced air quality measurement technologies. The new availability of real-time measurements of the many chemical constituents in PM<sub>2.5</sub>, and time-resolved particle size distributions in diverse U.S. locations, has the capacity to improve understanding of health effects associated with particulate matter exposure and contribute to building a foundation for protecting public health.

### Summary

#### What is already known about this topic?

Smoke is a complex mixture of gases and airborne particulate matter; urban fires and conventional wildfires emit different air pollutants. The Atmospheric Science and Chemistry mEasurement NeTwork (ASCENT), a new, advanced air quality measurement network, provides real-time measurements of the chemical constituents in fine particulate matter (PM<sub>2.5</sub>).

#### What is added by this report?

During the January 2025 Los Angeles fires, ASCENT recorded an approximate 110-fold increase in PM<sub>2.5</sub> lead levels compared with values from the previous few days.

#### What are the implications for public health practice?

Urban fires emit air pollutants that pose risks different from those of conventional wildfires. It is important for epidemiologic studies to consider PM<sub>2.5</sub> composition when assessing the impacts of urban fire smoke exposure. Health officials should communicate protective measures to the public (monitor air quality forecasts and follow guidance by local emergency management officials).

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Corresponding authors: Haroula D. Baliaka, [haroula@caltech.edu](mailto:haroula@caltech.edu) and  
Nga L. Ng, [ng@chbe.gatech.edu](mailto:ng@chbe.gatech.edu).

<sup>1</sup>California Institute of Technology, Pasadena, California; <sup>2</sup>University of  
Riverside, Riverside California; <sup>3</sup>University of California Davis, Davis,  
California; <sup>4</sup>Georgia Institute of Technology, Atlanta, Georgia.

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