Methods of health risk and impact assessment at industrially contaminated sites: a systematic review

Kairong Xiong,[1,2] Andreja Kukec,[3,4] Isabell Katharina Rumrich,[1,5] Tanja Rejc,[4] Roberto Pasetto,[6] Ivano Iavarone,[6] Otto Hänninen[1]

[1] Department Public Health Solutions, National Institute for Health and Welfare, Kuopio (Finland)
[2] School of Environmental Science and Engineering, Guangdong University of Technology, Guangzhou (China)
[3] Faculty of Medicine, Department of Public Health, University of Ljubljana (Slovenia)
[4] National Institute of Public Health, Ljubljana (Slovenia)
[5] University of Eastern Finland, Department of Environmental and Biological Sciences, Kuopio (Finland)
[6] Department of Environment and Health, National Institute of Health, Rome (Italy)

Corresponding author: Otto Hänninen; otto.hanninen@thl.fi

ABSTRACT

BACKGROUND: this paper is based upon work from COST Action ICSHNet. Industrially contaminated sites (ICSs) are a serious problem worldwide and there is growing concern about their impacts on the environment and public health. Health risk assessment methods are used to characterize and quantify the health impacts on nearby populations and to guide public health interventions. However, heterogeneous methods and inconsistent reporting practices compromise comparability risk and impact estimates.

OBJECTIVES: to review the literature on assessment of the adverse health effects of ICSs. Specifically, we:

- collect published, peer-reviewed literature addressing health assessment of ICSs;
- identified and evaluated the methods and tools for the assessment of health impacts related to ICSs;
- analysed the methods and tools used in different conditions;
- discussed the strengths and weaknesses of the identified approaches;
- presented an up-to-date understanding of the available health risk and impact assessment in ICSs. In addition, the terminologies were described and harmonization was proposed.

METHODS: we systematically searched PubMed and Web of Science to identify peer-reviewed reviews and original studies from January 1989 to December 2017. We used a qualitative approach for analysing the different elements (type of ICSs, Country of research, active years of working, distance from sources, pollutants, affected population, methods and tools, health outcomes, main founding, method stage, dose-response assessment, risk characterization) of included studies. We divided risk assessment methods used in the papers into four stages: semi-quantitative, quantitative, health impact, and health burden stage.

RESULTS: a total of 92 relevant original papers at ICSs were found and analysed. In current practice, the health risks have been characterized mainly as hazard quotients or hazard indexes (23 studies), and as cancer risk probabilities (60 studies). Only 8 studies estimated the number of cases and one study evaluated years of life lost.

CONCLUSION: hazard quotients and cancer probabilities are suitable for semi-quantitative and quantitative personal risk estimation, respectively. More comparable risk characterization on public health level requires specificity on the type of outcome and corresponding number of cases. Such data is needed for prioritization of action at low to medium risk sites. We found limited amount of studies that have quantified the health impact at industrially contaminated sites. Most of the studies have used semi-quantitative risk characterization approaches and the adopted methods are mostly of toxicological origin, while epidemiological analysis is almost lacking. There is a need to improve quantitative risk assessment and include health impact and environmental burden of disease assessments at ICSs.

Keywords: health risk assessment, health impact assessment, contaminated sites, impact assessment, industry, methods

KEYPOINTS

What is already known

- **Health risk assessment extrapolating from exposures is the fastest way to health risk characterization.**
- **Since the health risk assessment paradigm formulation in the 1980's, the methods have been applied also at contaminated sites.**

What this paper adds

- **This paper presents a summary of methods applied at contaminated sites as they have been reported in the peer-reviewed literature and proposes a way forward.**
- **Development of burden of disease methodologies proposes substantial benefits towards more comparable presentation of risks.**
- **In the future, it would be necessary to follow-up the development of health risk assessment and health impact assessment, especially in conjunction with industrially contaminated sites; the researchers in this field should harmonize terminology.**

INTRODUCTION

Population exposure due to industrially contaminated sites (ICSs) is a global environmental health problem.[1] Contaminated sites result from past and present industrial activities, including the operation of factories, mines, smelters, electrical power plants, and other production facilities, municipal and medical waste incineration plants and harbours.[2,3] The term 'contaminated site' may, however, have different meanings. The World Health Organisation (WHO) gives a general operational definition of contaminated sites, based on a public health perspective, as "areas hosting or having hosted human activities which have produced or might produce environmental contamination of soil, surface or groundwater, air, and food chain, resulting or being able to result in human health impacts".[4]

Given this definition, an area affected by a single chemical contamination of a single environmental matrix (e.g., the soil contamination caused by a given pesticide) and a large area with soil, water, air, and food chain contamination by multiple chemicals (e.g., the contamination caused by long-term emissions of a petrochemical complex) can be both considered contaminated sites.

Industrial activity often results in soil contamination, which has been recognized as a serious problem requiring immediate actions. In Europe alone, the European Environment Information and Observation Network for Soil (EIONET-SOIL) has recorded 342,000 sites with contaminated soil and, in addition, over two million sites are suspected for potential contamination.[2] The number of contaminated sites can globally be expected to be millions since limited data are yet available for Eastern Europe, Africa, South America, Asia, and for key Countries such as China and India.[2]

According to the European estimates, industrial production and commercial service are the main cause of soil contamination (41.4% of identified sites), followed by municipal waste treatment and disposal (15.2%). Main contaminants include mineral oil (33.7% of contaminated sites) and heavy metals (37.3%), followed by polycyclic aromatic hydrocarbons, toxic volatile organic compounds, and chlorinated hydrocarbons.[5] It has to be acknowledged that the environmental performance of the European industry has improved in the last decades in terms of reducing emissions; however, the sector is still responsible for significant amounts of pollution to air, water, and soil, as well as generation of waste.[6]

An estimated 40 million Americans live within 6.4 km (4 miles) of contaminated sites (superfund sites, formally called comprehensive environmental response, compensation and liability act) requiring a long-term response to clean up hazardous material contaminations in the USA. About 11 million people live within 1.6 km from these superfund sites, 3 to 4 million of them are children under 18 years of age.[7] The amount of European population living close to contaminated sites is also large, as on average there are 5.7 contaminated sites (CSs) per 10,000 inhabitants, based on soil contamination data.[5] In Italy, for instance, approximately 5.5 million people reside in 44 contaminated sites of national concern for environmental remediation, and about one million are younger than 20 years.[8]

A broad range of health effects have been associated with living near contaminated sites and/or exposure to pollutants, such as cancer,[9-14] acute bronchitis, asthma, cardiovascular disease, increased allergies and congenital anomalies. The WHO estimated that 12.6 million deaths globally, representing 23% of all deaths in 2012, were attributable to the environmental risk factors.[15] Industrial contamination causes complex multipollutant exposures, potentially with acute and long term adverse health effects.[16]

However, the assessment of possible health impacts related to ICSs entails considerable challenges.[17] The challenges arise from the complex exposure patterns at ICSs, which are often situated close to urban and/or socially deprived areas. Additionally, exposure often refers to multiple pollution sources and a mixture of pollutants. The health conditions associated with ICSs have multifactorial aetiology, and the interactions with risk factors from the social environment (lifestyle) are largely unknown.[4]

For the assessment, the relevant exposures and associated endpoints must be known. Often available data are less than optimal and determine which methods can be used. The choice of pollutant and endpoint may also be influenced by the availability of regulatory benchmark concentrations (or doses) or dose response data. These data are essential to estimate the potential impact of exposure and magnitude of effect. A lot of studies about the health impact (HIA) or risk assessment (HRA) of the ICSs have been done, and a variety of methods and tools have been used. Many studies and assessments concern air pollutants, while investigations on the contribution from soil and water contamination, as well as those related to food chain, are less represented in the scientific literature. Moreover, there is scarce application of suitable approaches to face the complex exposure scenarios associated with mixtures of hazardous chemicals in different environmental media that typically characterise many industrial contaminated areas. Therefore, it is necessary to identify and evaluate the methods and tools adopted in these studies. In response to these environmental health challenges, the COST Action IS1408 on Industrially Contaminated Sites and Health Network (ICSHNet) has been launched.[18] The Action, which involves researchers and experts from 33 Countries, is centred on developing a common European framework for research and response on environmental health issues in industrially contaminated sites, and establishing a European network of experts and institutions involved in assessing the health impacts and/or managing remediation and response. This scientific review has been inspired by the Action objectives, and contributes to the identification of suitable methodologies for characterising the potential risks and impacts on health in ICSs that can fit to data and resources available in different regions and ICS scenarios across Europe and beyond.

HRA is the process to estimate the nature and probability of adverse potential health effects (current or future) in humans who may be exposed to hazardous chemicals in contaminated environmental media, in the past, now or in the future.[11] It includes 4 basic steps:

- **hazard characterization:** the evaluation of scientific information on the hazardous properties of environmental agents;
- **dose-response assessment:** examines the numerical relationship between exposure and effects;
- **exposure assessment:** the extent of human exposure to those agents;
- **risk characterization:** the product of the risk assessment is a statement regarding the probability that populations or exposed individuals will be harmed and to what degree.[19]

Risk characterization is the final and very important step of the HRA. It is to summarize and integrate information from hazard assessment, dose-response assessment, and exposure assessment, to synthesize an overall conclusion about risk.[20] This step of HRA involves combining the exposure quantities, the toxicity benchmarks available, to calculate the excess lifetime cancer risks (risk) and non-cancer hazards (hazard) for each of the pathways and receptors identified.[21]

According the definition from the WHO Gothenburg Consensus Paper from 1999 HIA is "a combination of procedures, methods, and tools by which a policy, program, or project may be judged as to its potential effects on the health of a population, and the distribution of those effects within the population".[22] It aims to produce the information that will help decision-makers to make choices that promote health and minimize the negative health outcomes. HIA is usually consisting of six steps:

1. **SCREENING:** define if HIA is needed;
2. **SCOPING:** identify the health impacts;
3. **ASSESSMENT:** identify the affected population and quantify the magnitude of positive and negative impacts;
4. **RECOMMENDATION:** strategies to manage health impacts;
5. **REPORTING:** communication of findings and recommendations;
6. **MONITORING AND EVALUATING.**

None of the identified 12 previous review papers summarized the overall risk assessment methods (see section S1 in the on-line supplementary material).

The overall objective of our work was to create an up-to-date summary of HIA and HRA methods as applied to ICSs in Europe and globally. To do this, we conducted a systematic search of original studies on quantitative HRA and HIA in industrially contaminated sites. Specifically, we wanted to identify, describe, and evaluate methods used in quantification of health risks and impacts. We discuss the strengths and weaknesses of the identified approaches, classify the studies by contamination type, by pollutants, region/continent, and finally give recommendations on developing and applying the identified methods towards quantitative health impact.

METHODS

STRATEGY STUDY SELECTION CRITERIA AND PROCESS

A systematic literature review was conducted in PubMed and Web of Science. English language articles published from January 1989 to December 2017 were included. Search terms were developed to identify studies by outcome and sources of pollution (contaminated sites) (table 1). To limit the number of occupational and worker's health studies, these terms were used as exclusion criteria. As a result of the original searches conducted on December 6th, 2017, a total of 325 papers in PubMed and 180 in Web of Science were identified (figure 1). After title and abstract screening and full-text review, 92 original articles are included in the final analysis (see the list of references of the original papers and on-line supplement 3 on study characteristics).

SELECTORS	SEARCH TERMS
Outcome	#1 (assessment AND health) #2 (impact) #3 (risk) #4 (cancer OR carcinoge* OR non-carcinoge* OR mortality OR morbidity)
Sites	#5 (polluted sit* OR contaminated sit* OR industrial sit*) #6 (refiner* OR mine OR mines OR mining OR quarr* OR harbor OR landfil* OR incinerat* OR sawmill OR waste dumps OR glasswor* sit* OR foundr* OR waste combustion plan* OR sewage plan* OR steel plan* OR petrochemical plan* OR coke works OR processing plan* OR cement plan*)
Exclusions	#7 (occupational OR workers OR worker OR miners)

DATABASE	SEARCH STRATEGY	COVERAGE
PubMed	#8 (#1 AND(#2 OR #3) AND #4 AND (#5 OR #6) NOT #7)	Title and abstract
Web of science	#9 (#1 AND(#2 OR #3) AND (#4 OR #5))	Title[a]

[a] Abstracts not included in the database

Table 1. Search terms used in definition of the search strategies in PubMed and Web of Science.

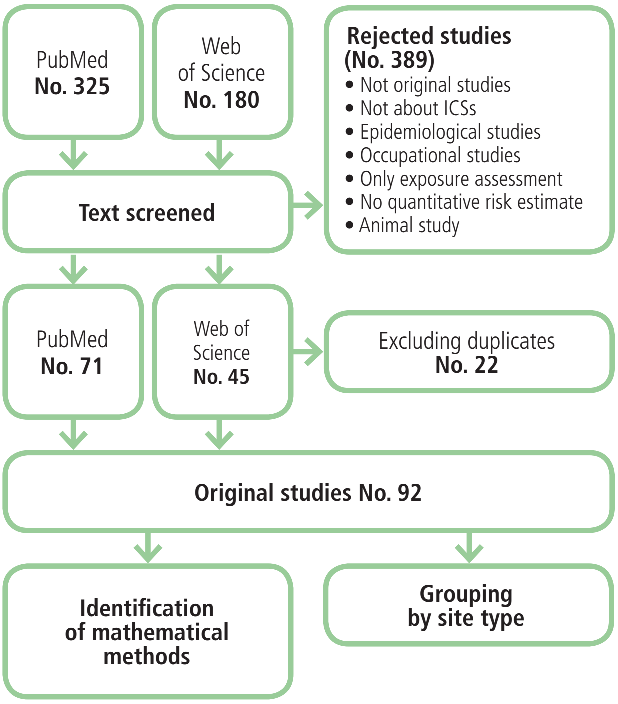

Figure 1. Flowchart of the literature research and grouping by the methods and site types.

In the screening, the original papers were sub-grouped by site types. Almost half of the studies were conducted at mining sites (42 studies), followed by heterogeneous group of different types of industries, including five cement plants, a chromate plant, a coking plant, an electronic appliances factory, a fertilizer plant, a glasswork, a harbour, three metal smelters, three refineries, a power plant, an organic chemical plant, and twelve industrial complexes.

SUMMARY OF THE MATHEMATICAL METHODS

Risk assessment methods applied in the papers were grouped into four stages (table 2, box 1). On the first level (stage 1, eq. 1a-b), the exposures or doses are compared with corresponding reference levels to produce a hazard quotient. Stage-2 methods estimate risk probabilities (eq. 2) using, e.g., cancer slope factor (CSF), cancer risk factor (CRF) or unit risk factor (UR, URF), typically per lifetime exposure of an individual. These approaches at stages 1-2, originating from the US Environmental Protection Agency (EPA),[11-14] do not typically report the type of health impact (non-cancer endpoints) or type of cancer (i.e., results are expressed as any cancer or total cancer).

Accounting for the size of the exposed population in addition to the risk probability and potentially the background incidence of the endpoints, it is possible to es-

STAGE	INFORMATION NEEDED		OUTPUTS
	TOXICITY	HEALTH	
1. Semi-quantitative	Reference level	None	Hazard quotient and index
2. Quantitative	Cancer slope	None	Lifetime cancer probability
3. Health impact	Relative risk	Incidence rate	Attributable incidence
4. Health burden	–"–	+ life expectancy	Years of life lost

Table 2. Grouping of methods used to characterize the health risk and impact.

BOX 1. MATHEMATICAL APPROACHES USED IN HEALTH RISK ASSESSMENT

Semi-quantitative methods generally used for non-cancer risks
Hazard quotient; exposure, reference level

(1a) $$HQ_i = \frac{E}{Rf}$$

HQ: hazard quotient
E: exposure
Rf: reference level

Hazard index (cumulative over hazard quotients)

(1b) $$HI = \sum_i HQ_i$$

HI: hazard index
HQ: hazard quotient

Quantitative risk
Especially cancer risks are typically estimated as cancer probability

(2) $$p = E \times UR$$

P: probability
E: exposure
UR: unit risk

Number of cases (HIA)
Unit risk model for attributable incidence (cases)

(3) $$AI = E \times UR \times N$$

AI: attributable incidence (No. of cases)
E: exposure
UR: unit risk
N: population size (persons)

Attributable incidence (cases) (excess risk approach)

(4) $$AI = (RR_E - 1) \times BR$$

AI: attributable incidence
RR: relative risk of exposed population
BR: background rate

METHOD STAGES	INDUSTRIAL SITES		WASTE AND RECYCLING		STUDIES
	MINE	FACTORIES[a]	INCINERATOR[b]	LANDFILL	
1. Semi quantitative risk (HQ)	18	4	0	1	23
2. Cancer risk probability (p)	21	26	6	7	60
3. Health impact (n)	3	1	4	0	8
4. Health impact (YLL)	0	0	1	0	1
Original studies by site type	42	31	11	8	92

[a] Including ten types of industries and industrial complexes (see the "Methods" section for details).
[b] Several incinerator studies included also landfill sites.
HQ: hazard quotient; **p:** probability; **n:** number of cases; **YLL:** years of life lost

Table 3. Original studies grouped by mathematical methods and by site types.

GROUP	POLLUTANT
Criteria air pollutants and inorganic substances	Nitrogen dioxide (NO_2), particulate matter 10 micrometers or less in diameter (PM_{10}), particulate matter 2.5 micrometers or less in diameter ($PM_{2.5}$), sulfur dioxide (SO_2), total suspended particles (TSP), asbestos, cyanide, hydrogen chloride (HCl), hydrogen fluoride (HF)
Metals	Aluminium (Al), antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), boron (B), cadmium (Cd), chromium (Cr), copper (Cu), cobalt (Co), gold (Au), lead (Pb), lithium (Li), iron (Fe), manganese (Mn), mercury (Hg), molybdenum(Mo), nickel (Ni), phosphorus (P), scandium (Sc), silver (Ag), selenium (Se), strontium (Sr), thorium (Th), thallium (Tl), tin (Sn), titanium (Ti), uranium (U), vanadium (V), zinc (Zn)
Dioxins and furans (PCDD/Fs)	Dioxins and furans as toxic equivalents (TEQ)
Chlorinated monocyclic aromatics	1,2-dichlorobenzene, 1,2,4,5-tetrachlorobenzene, 1,2,4-trichlorobenzene, pentachlorophenol, hexachlorobenzene, pentachlorobenzene 2,3,4,6-tetrachlorophenol, 2,4,6-trichlorophenol, 2,4-dichlorophenol
Polycyclic aromatic hydrocarbons (PAHs)	Acenaphthylene, acenaphthene, anthracene, benzo(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)fluorene, benzo(b)fluorene, benzo(ghi)perylene, benzo(e)pyrene, chrysene, dibenzo(a,c)anthracene, dibenzo(a,h)anthracene, fluoranthene, fluorene, indeno(1,2,3-cd)pyrene, perylene, phenanthrene, pyrene, 1-methylnaphthalene, 2-methylnaphthalene, naphthalene
Volatile organic compounds (VOCs)	Acetaldehyde, benzene, biphenyl, bromodichloromethane, bromomethane, dichlorodifluoromethane, dichloroethene, 1,1-ethylbenzene, ethylene dibromide (1,2 dibromoethane), formaldehyde, tetrachloroethylene, toluene, trichloroethylene, 1,1,2, vinyl chloride (chloroethene), xylenes, m-, p- and o-bromoform (tribromomethane), carbon tetrachloride, chloroform, dichloromethane, o-terphenyl, trichloroethane, 1,1,1-trichlorofluoromethane

Note: see the separate list of references of the original papers; see S3 on-line supplementary material to consult the characteristics of the original studies.

Table 4. Total of 95 pollutants divided into six groups considered in the original papers.

HEALTH ENDPOINTS	POLLUTANT*
NON-SPECIFIC CANCER:	
Any cancer	dioxins,[10,22] PAH,[12] PM_{10},[19] Cd,[83] Ni,[6] Cr,[47] NO_2, As[71]
SPECIFIC TYPE OF CANCER:	
Lung cancer	asbestos,[7] PM_{10},[12] Cd,[22]
Mesothelioma	asbestos,[7]
NON-SPECIFIC OUTCOMES:	
Non-cancer	Hg, Pb,[10] Cd, [6,12] dioxins,[45,47,53] Zn,[71] As[78]
Morbidity	PM_{10}[12]
SPECIFIC NON-CARCINOGENIC OUTCOMES:	
acute bronchitis	PM_{10}[12]
asthma	PM_{10}[12], NO_2[71]
cardiovascular effects	VOC[6]
congenital anomalies	PM_{10}[19]
chronic obstructive pulmonary disease	SO_2[71]
developmental risks	dioxins[22]
haematological effects	VOC[6]
irritation of the respiratory system	SO_2, HCl[22]
low birth weight[19]	PM_{10}[19]
neuro-behavioural effects	VOC,[6] Hg, Pb[22]
renal effects	VOC,[6] Cd[22]
MORTALITY OUTCOMES:	
Mortality	PM_{10},[12] SO_2[71]
YoLL	PM_{10}[19]

PAH: polycyclic aromatic hydrocarbon; **VOC:** volatile organic compounds; **YoLL:** years of life lost
Note: the superscript numbers refer to the list of references of the original papers.

Table 5. Health endpoints covered in the 92 original studies with some examples of pollutant associations.

timate the number of cases (stage 3; eq. 3). Finally, for premature mortality outcomes, the fourth stage estimates the number of life years lost (eq. 4).

We used qualitative approach for analysing the different elements of included studies: type of ICSs, Country of research, active years of working, distance from sources, pollutants, affected population, methods and tools, health outcomes, main founding, method stage, dose-response assessment, risk characterization.

RESULTS AND DISCUSSION

In the articles, we identified the mathematical methods. The most often applied method was characterization of cancer risk as probability (60 studies; 65%) (table 3). Second largest number of studies characterized non-cancer risks using hazard quotient and hazard indexes (23 studies; 25%) (table 3). HIA has been reported only in a small fraction of articles (10%). Number of cases of identified disease or endpoint was estimated in eight studies (9%). Stage 4 assessment, which includes the application of WHO's burden of disease methodology, has been reported only once. The study quantified the health impact of premature all-cause mortality as number of years of life lost.[23]

Almost all the studies followed US EPA for the characterization of the health risk at ICSs, and characterized toxicity with cancer slope factor and reference doses from Agency for Toxic Substances and Disease Registry (ATSDR) and International Agency for Research on Cancer (IARC), 2 study in Europe also compared WHO office for air quality,[24, 25] Uddh-Soderberg et al. used the reference from Swedish EPA.[26] For carcinogen pollutants, risk estimates represent the incremental probability that an individual will develop cancer over a lifetime as a result of a specific exposure to a carcinogenic chemical.[9]

DIFFERENT SITE TYPES

The original studies were divided into four groups by the type of industrial contamination. Largest group consists of mining sites (42 original studies), followed by different types of factories and industrial complexes (31 original studies), industrial and municipality waste incinerators (11 original studies), and landfill sites (8 original studies) (table 3). Various types of industries and industrial complexes were associated with industrial contamination in the identified studies: cement plants (4 studies), chromate plants (1 study), coking plants (1 study), electronic appliances factories (1 study), fertilizer plants (1 study), glassworks (1 study), metal smelters (2 studies), chemical plants (1 study), refineries (2 studies), power plants (1 study), other industrial areas (8 studies).

The identified studies originated from nearly all continents. Best represented was Europe, covering nearly all the different site types with 35 studies (38%), except some heterogeneous group of different types of factories. Over 90% of the incinerator studies were performed in Europe and about 74% of the mining studies come from Africa (21%) and Asia (55%). This geographical imbalance may be partly responsible for the corresponding site type specific differences in the mathematical methods applied: 78% of the mining site studies applied hazard quotient methods, while none of the incinerator studies did.

Pollutants at industrially contaminated sites

Given the similarity between contaminating industrial activities in the same site type, they have the most prevalent pollutants in common (table 4) (see table S3.1 and S3.2, on-line supplementary material). For mines, the main assessed contaminants are metals. Of the 42 studies about mines, 28 studies evaluated the health risk of lead; 27 studies evaluated arsenic and cadmium, followed by copper, zinc, chromium, nickel, mercury, cobalt, manganese, iron, vanadium, barium, and molybdenum. Asbestos, cyanide, and polycyclic aromatic hydrocarbons (PAHs) was evaluated by 1 study, respectively. For incinerators, the main contaminants assessed were dioxins and some heavy metals (such as cadmium, mercury, lead, nickel, and arsenic), together with particulate matter 10 micrometres or less in diameter (PM_{10}) and PAHs. Common pollutants assessed in landfills are volatile organic compounds (VOCs), dioxins, PAHs, and some heavy metals (such as lead and chromium). As two studies of cement plants belong to Spain, the contaminants assessed are similar as dioxins, PM_{10}, nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and metals. Both one study for glassworks and one for fertilizer plants selected arsenic as a main contaminant to assess the health risk.

Most studies looked at pollutants in soil, 25 studies based only on soil, and 33 studies analysed mixture environmental media samples including soil. Nine of the latter studies included vegetables and fruits. Metals were the most evaluated pollutants at mines. 15 studies investigated only air and 10 studies only water. For waste and recycling sites, air pollutants were often evaluated. Three studies evaluated sediment samples, 1 study house dust, and 2 studies road dust. Only 2 studies collected biomonitoring (hair and urine) samples.

Health endpoints assessed in the original papers

Health effects related to the site contamination depend on the nature of the contaminant, the level of exposure, and the vulnerability of the individual affected.[27] The health endpoints used in the studies usually expressed as cancer or non-cancer, while a few studies also specify as any cancer, lung cancer, and mesothelioma; acute bronchitis and asthma (table 5).

TERMINOLOGY

The terminology used in the identified studies may be at places ambiguous or using slightly different terms for similar meaning, as shown by these examples for exposure/dose, toxicity/carcinogenicity, and resulting risk. Chronic daily intake (CDI) is used to estimate the intake (via ingestion) of a chemical during a specific time period and lifetime average daily dose (LADD) for carcinogenic chemicals to take the lifelong effect into account.[13]

US EPA uses terms slope factor seemingly synonymously with cancer slope factor.[13] Similar terms used in the studies include cancer slope factor (CSF), which is used to calculate ingestion cancer risk, and unit risk factor (URF) or inhalation cancer risk calculation,[13] and the term was harmonized by WHO as slope factor (SF) for oral slope factor and slope factor in relation to a concentration of a chemical in air or in water.[24]

Cancer risks are expressed using terms such as incremental lifetime-risk,[28] individual lifetime excess risk,[29] excess lifetime cancer risks,[30] total carcinogenic risks (TCR),[31] individual cancer risk (ICR),[32] lifetime cancer risk (LCR), incremental lifetime cancer risks (ILCR),[33] individual risk (IR),[34] annual incremental risk,[35] and individual excess cancer risk (IECR).[36]

For a summary of terms used in the original papers see on-line supplementary material S2.

LIMITATIONS AND RECOMMENDATIONS

Current work collects, discusses, and reviews different methodological approaches to HRA and tries to build a basic methodological approach to conduct HRA. Nevertheless, it is conceivable that a number of scientific papers have been published in journals which are not indexed in PubMed or Web of Science or they used a different terminology than HRA and consequently were not included in this review. HIA method stages 1 and 2 are often required by the legal framework for ICSs and might not be reported in scientific articles, but in administrative reports. Peer-reviewed scientific publications are necessary for developing the field and should be encouraged. Overall, a positive trend emerged with increasing numbers of studies published in peer-reviewed journals in recent years. From the included studies, only 22% (21 out of 92) were published before 2010, while 53% (49 out of 92) were published between 2015 and 2017.

Data availability may dictate which identified methods can be used for HRA since the data needs increase from stage 1 to 4. Stages 1 and 2 require only exposure (or concentration or dose) information and related reference values, which are routinely available from databases. Stages 3 and 4, however, also require incidence data, which may not be routinely available for the contaminated area. HIA would greatly benefit from routine collection of morbidity/mortality information in combination with spatial information. Cancer registers are well established in many high-income Countries and can serve as an example for routine collection of such required data. In the future, it would be necessary to follow up the development of the HRA and HIA, especially in conjunction with ICSs. The researchers in this field should prepare the set of some rules suggestions for the use of terminology.

Contaminated sites may also produce unpleasant odours which should also be considered as one of the pollutants at ICSs.[38] The obnoxious odours generated from industries are a complex mixture of gases present at higher concentrations, dust, and vapours. Odour emissions may be difficult to quantify objectively. Odour nuisance may also have direct and indirect impacts on health. Among the symptoms caused by unpleasant odours, there are the symptoms of classical stress response, nausea, fatigue, irritations (eyes, nose, and throat), sleep disturbance, and inability to concentrate.[38-40]

Application of environmental burden of disease methods, including preclinical, or perceived, health end points, such as odour, headaches, cognitive performance, as well as effects in sensitive time windows and health consequences later in life should be promoted for better comparability and more complete understanding of the health implications.

CONCLUSIONS

The present report is, to our knowledge, the first systematic review on health risk and impact assessment methods related to industrially contaminated sites.

Systematic search of HRA methods at ICSs produced a total of 92 original papers published between 1989 and 2017 covering waste, incinerator, mining, and a group of various types of industrial sites. The most commonly used type of risk characterization was lifetime risk probability of (any) cancer, followed by hazard quotients and indexes. Only eight studies estimated the number of cases of specified diseases and only one calculated the years of life lost that would allow for quantitative comparison of mortality risks between sites. This result highlights the toxicological origin of the utilized methods and lack of epidemiological estimates that would be necessary also for wider application of relative-risk-based health risk characterization. A parallel review is conducted on summarizing the epidemiological approaches used in the literature to be published in this same issue (De Sario et al.; pp. 59-68).

While the basic methods used were mathematically identical, the terminology used in different contexts was extremely heterogeneous and will benefit from harmonization. In this study, we did not analyse and compare the estimated magnitude of health risks by different pollutants, endpoints or site types. This would be a meaningful follow-up approach.

The results of this work contribute to address the main objective of ICSHNet COST Action which is the identification of sound methodologies for health risk and impact assessment in the development of guidance documents on how to face the heterogeneous environmental health scenarios of ICS across participating Countries.

Conflict of interest disclosure: the authors declare they have no conflict of interest.

Acknowledgements: this work was supported by National Social Science Foundation of China (grant number 17BXW104), the COST Action IS1408 grants for short term scientific missions, the Juho Vainio Foundation (201710136), personal grant for IKR from the Finnish Cultural Foundation North Savo Regional Fund (grant number 65161550), and intramural funding by the participating institutes.

REFERENCES

1. Carpenter DO, Arcaro KF, Bush B, Niemi WD, Pang S, Vakharia DD. Human health and chemical mixtures: an overview. Environ Health Perspect 1998;106 Suppl 6:1263-70.
2. Panagos P, Van Liedekerke M, Yigini Y, Montanarella L. Contaminated sites in Europe: review of the current situation based on data collected through a European network. J Environ Public Health 2013;2013:158764. (*review*)
   Panagiotakis I, Dermatas D. Remediation of contaminated sites. Bull Environ Contam Toxicol 2015;94(3):267-68. (*remediation*)
3. Brandon E. The Nature and Extent of Site Contamination. In: Brandon E. Global Approaches to Site Contamination Law. Springer 2013; pp. 11-39.
4. WHO Regional Office for Europe. Contaminated sites and health. Report of two WHO workshops: Syracuse, Italy, 18 November 2011; Catania, Italy, 21-22 June 2012. Copenhagen (Denmark): WHO Regional Office for Europe; 2013. Available from: http://www.euro.who.int/__data/assets/pdf_file/0003/186240/e96843e.pdf?ua=1
5. European Environment Agency. CSI 015: progress in management of contaminated sites. Copenhagen: European Communities; 2017. Available from: https://www.eea.europa.eu/data-and-maps/indicators/progress-in-management-of-contaminated-sites-3/assessment/download.pdf
6. European Environmental Agency. SOER 2015 – The European environment – state and outlook 2015. Synthesis report. Copenhagen: European Environment Agency; 2015. Available from: www.eea.europa.eu/soer (last accessed: 18.04.2018).
7. Landrigan PJ, Wright RO, Cordero JF, et al. The NIEHS Superfund Research Program: 25 Years of Translational Research for Public Health. Environ Health Perspect 2015;123(10):909-18.
8. Iavarone I, Pirastu R, Minelli G, Comba P. Children's health in Italian polluted sites. Epidemiol Prev 2013;37(1) Suppl 1:255-60.
9. World Health Organization. Air Quality Guidelines. Global Update 2005. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide. Copenhagen: WHO Regional Office for Europe; 2006. Available from: http://www.euro.who.int/__data/assets/pdf_file/0005/78638/E90038.pdf
10. World Health Organization. Population health and waste management: scientific data and policy options. Report of a WHO Workshop: Rome, Italy, 29-30 March 2017. Copenhagen: WHO Regional Office for Europe; 2007. Available from: http://www.euro.who.int/__data/assets/pdf_file/0012/91101/E91021.pdf
11. United States Environmental Protection Agency. Risk Assessment Guidance for Superfund (RAGS). Human Health Evaluation Manual. Washington DC: US EPA; 1989.
12. United States Environmental Protection Agency. Proposed Guidelines for Carcinogen Risk Assessment. US EPA: Washington; DC 1996.
13. United States Environmental Protection Agency. Human health risk assessment protocol for hazardous waste combustion facilities. Washington DC: US EPA; 2005.
14. United States Environmental Protection Agency. Risk Assessment Guidance for Superfund (RAGS). Part A: Human Health Evaluation Manual; Part E: Supplemental Guidance for Dermal Risk Assessment; Part F: Supplemental Guidance for Inhalation Risk Assessment. Washington DC: US EPA; 2009.
15. World Health Organization. A global assessment of the burden of disease from environmental risks. Geneva: WHO; 2006.
16. Pasetto R, Martin-Olmedo P, Martuzzi M, Iavarone I. Exploring available options in characterising the health impact of industrially contaminated sites. Ann Ist Super Sanita 2016;52(4):476-82.
17. Martuzzi M, Pasetto R, Martin-Olmedo P. Industrially contaminated sites and health. J Environ Public Health 2014;2014;198574.
18. COST Action IS1408 Industrially Contaminated Sites and Health Network. Available from: https://www.icshnet.eu/ (last accessed: 10.04.2018).
19. United States Environmental Protection Agency. Risk characterization handbook. Washington DC, US EPA, 2000.
20. United States Environmental Protection Agency. A Framework for Assessing Health Risks of Environmental Exposures to Children. Washington DC, US EPA, 2006.
21. United States Environmental Protection Agency. Risk Assessment Guidance for Superfund Sites; Volume III - Part A: Process for Conducting Probabilistic Risk Assessment. Washington DC, US EPA, 2001.
22. World Health Organization. Health Impact Assessment. Main concepts and suggested approaches. Gothenburg Consensus Paper. December 1999. Available from: http://www.impactsante.ch/pdf/HIA_Gothenburg_consensus_paper_1999
23. Forastiere F, Badaloni C, de Hoogh K, et al. Health impact assessment of waste management facilities in three European countries. Environ Health 2011;10:53.
24. Boudet C, Zmirou D, Laffond M, Balducci F, Benoit-Guyod J. Health risk assessment of a modern municipal waste incinerator. Risk Anal 1999;19(6):1215-22.
25. Cordioli M, Vincenzi S, De Leo GA. Effects of heat recovery for district heating on waste incineration health impact: a simulation study in Northern Italy. Sci Total Environ 2013;444:369-80.
26. Uddh-Soderberg TE, Gunnarsson SJ, Hogmalm KJ, Lindegard MIBG, Augustsson ALM. An assessment of health risks associated with arsenic exposure via consumption of homegrown vegetables near contaminated glassworks sites. Sci Total Environ 2015;536:189-97.
27. European Environment Agency. Europe's environment: the fourth assessment. European Communities. Copenhagen: EEA; 2007. Available from: https://www.eea.europa.eu/publications/state_of_environment_report_2007_1
28. Bourgault MH, Gagné M, Valcke M. Lung cancer and mesothelioma risk assessment for a population environmentally exposed to asbestos. Int J Hyg Environ Health 2014;217(2-3):340-46.
29. Glorennec P, Zmirou D, Bard D. Public health benefits of compliance with current E.U. emissions standards for municipal waste incinerators: a health risk assessment with the CalTox multimedia exposure model. Environ Int 2005;31(5):693-701.
30. Kaetzel RS, Yost LJ, O'Boyle RA, Booth PN. Risk Assessment as a decision-making tool for treatment of emissions at a new aluminum smelter in Iceland: 2. Human Health Risk Assessment. Hum Ecol Risk Assess 2009;15(3):442-68.
31. Mari M, Rovira J, Sanchez-Soberon F, Nadal M, Schuhmacher M, Domingo JL. Environmental trends of metals and PCDD/Fs around a cement plant after alternative fuel implementation: human health risk assessment. Environ Sci Process Impacts 2017;19(7):917-27.
32. Morselli L, Passarini F, Piccari L, Vassura I, Bernardi E. Risk assessment applied to air emissions from a medium-sized Italian MSW incinerator. Waste Manag Res 2011;29(10) Suppl:48-56.
33. Ollson CA, Knopper LD, Whitfield Aslund ML, Jayasinghe R. Site specific risk assessment of an energy-from-waste thermal treatment facility in Durham Region, Ontario, Canada. Part A: Human health risk assessment. Sci Total Environ 2014;466-467:345-56.
34. Perrodin Y, Donguy G, Emmanuel E, Winiarski T. Health risk assessment linked to filling coastal quarries with treated dredged seaport sediments. Sci Total Environ 2014;485-6:387-95.
35. Schuhmacher M, Domingo JL, Garreta J. Pollutants emitted by a cement plant: health

risks for the population living in the neighborhood. Environ Res 2004;95(2):198-206.
36. Zakharova T, Tatano F, Menshikov V. Health cancer risk assessment for arsenic exposure in potentially contaminated areas by fertilizer plants: a possible regulatory approach applied to a case study in Moscow region-Russia. Regul Toxicol Pharmacol 2002;36(1):22-33.
37. World Health Organization. WHO Human Health Risk Assessment Toolkit: Chemical Hazards. Ottawa: WHO; 2010. Available from: http://www.inchem.org/documents/harmproj/harmproj/harmproj8.pdf
38. Nicell JA. Assessment and regulation of odour impacts. Atmos Environ 2009;43: 196 -206.
39. McGinley MA, McGinley CM. The "grey line" between odour nuisance and health effects. In: Proceedings of Air and Waste Management Association 92nd Annual Meeting and Exhibition. St. Louis, 20-24 June 1999. Available from: http://fivesenses.com/Documents/Library/23%20%20Gray%20Line%20Nusance%20Health.pdf
40. Badach J, Kolasi'ska P, Paciorek M, et al. A case study of odour nuisance evaluation in the context of integrated urban planning. J Environ Manage 2018;213:417-24.

LIST OF ORIGINAL PAPERS

1. Allan SE, Sower GJ, Anderson KA. Estimating risk at a Superfund site using passive sampling devices as biological surrogates in human health risk models. Chemosphere 2011;85(6):920-27.
2. Avila PF, da Silva EF, Candeias C. Health risk assessment through consumption of vegetables rich in heavy metals: the case study of the surrounding villages from Panasqueira mine, Central Portugal. Environ Geochem Health 2017;39(3):565-89.
3. Bejaoui I, Kolsi-Benzina N, Sappin-Didier V, Munoz M. Health Risk Assessment in Calcareous Agricultural Soils Contaminated by Metallic Mining Activity Under Mediterranean Climate. Clean-Soil Air Water 2016;44(10):1385-95.
4. Bempah CK, Ewusi A. Heavy metals contamination and human health risk assessment around Obuasi gold mine in Ghana. Environ Monit Assess 2016;188(5):261.
5. Bortey-Sam N, Nakayama SM, Ikenaka Y, et al. Health risk assessment of heavy metals and metalloid in drinking water from communities near gold mines in Tarkwa, Ghana. Environ Monit Assess 2015;187(7):397.
6. Boudet C, Zmirou D, Laffond M, Balducci F, Benoit-Guyod J. Health risk assessment of a modern municipal waste incinerator. Risk Analysis 1999;19(6):1215-22.
7. Bourgault MH, Gagne M, Valcke M. Lung cancer and mesothelioma risk assessment for a population environmentally exposed to asbestos. Int J Hyg Environ Health 2014;217(2-3):340-46.
8. Briki M, Zhu Y, Gao Y, Shao M, Ding H, Ji H. Distribution and health risk assessment to heavy metals near smelting and mining areas of Hezhang, China. Environ Monit Assess 2017;189(9):458.
9. Cai LM, Xu ZC, Qi JY, Feng ZZ, Xiang TS. Assessment of exposure to heavy metals and health risks among residents near Tonglushan mine in Hubei, China. Chemosphere 2015;127:127-35.
10. Cangialosi F, Intini G, Liberti L, Notarnicola M, Stellacci P. Health risk assessment of air emissions from a municipal solid waste incineration plant--a case study. Waste Manag 2008;28(5):885-95.
11. Cheng X, Huang Y, Long Z, Ni S, Shi Z, Zhang C. Characteristics, Sources and Health Risk Assessment of Trace Metals in PM10 in Panzhihua, China. Bull Environ Contam Toxicol 2017;98(1):76-83.
12. Cordioli M, Vincenzi S, De Leo GA. Effects of heat recovery for district heating on waste incineration health impact: a simulation study in Northern Italy. Sci Total Environ 2013;444:369-380.
13. Davoli E, Fattore E, Paiano V, et al. Waste management health risk assessment: a case study of a solid waste landfill in South Italy. Waste Manag 2010;30(8-9):1608-13.
14. de Souza ES, Texeira RA, Cardoso da Costa HS, et al. Assessment of risk to human health from simultaneous exposure to multiple contaminants in an artisanal gold mine in Serra Pelada, Para, Brazil. Sci Total Environ 2017;576:683-695.
15. Donoghue AM, Coffey PS. Health risk assessments for alumina refineries. J Occup Environ Med 2014;56(5):S18-22.
16. Durmusoglu E, Taspinar F, Karademir A. Health risk assessment of BTEX emissions in the landfill environment. J Hazard Mater 2010;176(1-3):870-77.
17. El Hamiani O, El Khalil H, Sirguey C, et al. Metal Concentrations in Plants from Mining Areas in South Morocco: Health Risks Assessment of Consumption of Edible and Aromatic Plants. Clean-Soil Air Water 2015;43(3):399-407.
18. Fan Y, Zhu T, Li M, He J, Huang R. Heavy Metal Contamination in Soil and Brown Rice and Human Health Risk Assessment near Three Mining Areas in Central China. J Healthc Eng 2017;2017:4124302.
19. Forastiere F, Badaloni C, de Hoogh K, et al. Health impact assessment of waste management facilities in three European countries. Environ Health 2011;10:53.
20. Gabari V, Carlos Fernandez-Caliani J. Assessment of trace element pollution and human health risks associated with cultivation of mine soil: A case study in the Iberian Pyrite Belt. Hum Ecol Risk Assess 2017;23(8):2069-86.
21. Giri S, Singh AK. Human health risk assessment due to dietary intake of heavy metals through rice in the mining areas of Singhbhum Copper Belt, India. Environ Sci Pollut Res Int 2017;24(17):14945-56.
22. Glorennec P, Zmirou D, Bard D. Public health benefits of compliance with current E.U. emissions standards for municipal waste incinerators: a health risk assessment with the CalTox multimedia exposure model. Environ Int 2005;31(5):693-701.
23. Hou W, Zhang L, Li Y, et al. Distribution and Health Risk Assessment of Polycyclic Aromatic Hydrocarbons in Soil from a Typical Contaminated Urban Coking Sites in Shenyang City. Bull Environ Contam Toxicol 2015;95(6):815-21.
24. Hu B, Wang J, Jin B, Li Y, Shi Z. Assessment of the potential health risks of heavy metals in soils in a coastal industrial region of the Yangtze River Delta. Environ Sci Pollut Res Int 2017;24(24):19816-26.
25. Hung ML, Wu SY, Chen YC, Shih HC, Yu YH, Ma HW. The Health Risk assessment of Pb and Cr leached from fly ash monolith landfill. J Hazard Mater 2009;172(1):316-23.
26. Ihedioha JN, Ukoha PO, Ekere NR. Ecological and human health risk assessment of heavy metal contamination in soil of a municipal solid waste dump in Uyo, Nigeria. Environ Geochem Health 2017;39(3):497-515.
27. Jia J, Li X, Wu P, et al. Human Health Risk Assessment and Safety Threshold of Harmful Trace Elements in the Soil Environment of the Wulantuga Open-Cast Coal Mine. Minerals 2015;5(4):837-48.
28. Jiang Y, Chao S, Liu J, et al. Source apportionment and health risk assessment of heavy metals in soil for a township in Jiangsu Province, China. Chemosphere 2017; 168:1658-68.
29. Kaetzel RS, Yost LJ, O'Boyle RA, Booth PN. Risk Assessment as a Decision-Making Tool for Treatment of Emissions at a New Aluminum Smelter in Iceland: 2. Human Health Risk Assessment. Hum Ecol Risk Assess 2009;15(3):442-68.
30. Kamunda C, Mathuthu M, Madhuku M. Health Risk Assessment of Heavy Metals in Soils from Witwatersrand Gold Mining Basin, South Africa. Int J Environ Res Public Health 2016;13(7):E663.
31. Kao WY, Ma HW, Wang LC, Chang-Chien GP. Site-specific health risk assessment of dioxins and furans in an industrial region with numerous emission sources. J Hazard Mater 2007;145(3):471-81.
32. Krishna AK, Mohan KR. Risk assessment of heavy metals and their source distribution in waters of a contaminated industrial site. Environ Sci Pollut Res Int 2014;21(5):3653-69.
33. Lee JS, Chon HT, Kim KW. Human risk assessment of As, Cd, Cu and Zn in the abandoned metal mine site. Environ Geochem Health 2005;27(2):185-91.
34. Lee LJ, Chan CC, Chung CW, Ma YC, Wang GS, Wang JD. Health risk assessment on residents exposed to chlorinated hydrocarbons contaminated in groundwater of a hazardous waste site. J Toxicol Environ Health A 2002;65(3-4):219-35.
35. Lee SW, Lee BT, Kim JY, Kim KW, Lee JS. Human risk assessment for heavy metals and as contamination in the abandoned metal mine areas, Korea. Environ Monit Assess 2006;119(1-3):233-44.
36. Li Kexin, Liang Tao, Wang Lingqing, Yang Zhiping. Contamination and health risk assessment of heavy metals in road dust in Bayan Obo Mining Region in Inner Mongolia, North China. Journal of Geographical Sciences 2015;25(12):1439-51.
37. Li F, Zhang J, Jiang W, et al. Spatial health risk assessment and hierarchical risk management for mercury in soils from a typical contaminated site, China. Environ Geochem Health 2017;39(4):923-34.
38. Li J, Wei Y, Zhao L, et al. Bioaccessibility of antimony and arsenic in highly polluted soils of the mine area and health risk assessment associated with oral ingestion exposure. Ecotoxicol Environ Saf 2014;110:308-15.
39. Lim H, Lee J, Chon H, Sager M. Heavy metal contamination and health risk assessment in the vicinity of the abandoned Songcheon Au-Ag mine in Korea. J Geochem Explor 2008;96(2-3):223-30.
40. Liu C, Lu L, Huang T, Huang Y, Ding L, Zhao W. The Distribution and Health Risk Assessment of Metals in Soils in the Vicinity of Industrial Sites in Dongguan, China. Int J Environ Res Public Health 2016;13(8):E832.
41. Liu G, Niu J, Zhang C, Guo G. Characterization and assessment of contaminated soil and groundwater at an organic chemical plant site in Chongqing, Southwest China. Environ Geochem Health 2016;38(2):607-18.
42. Mari M, Nadal M, Schuhmacher M, Domingo JL. Exposure to heavy metals and PCDD/Fs by the population living in the vicinity of a hazardous waste landfill in Catalonia, Spain: health risk assessment. Environ Int 2009;35(7):1034-39.
43. Mari M, Rovira J, Sanchez-Soberon F, Nadal M, Schuhmacher M, Domingo JL. Environmental trends of metals and PCDD/Fs around a cement plant after alternative fuel implementation: human health risk assessment. Environ Sci Process Impacts 2017;19(7):917-27.
44. Marti V, Jubany I, Perez C, Rubio X, De Pablo J, Gimenez J. Human Health Risk Assessment of a landfill based on volatile organic compounds emission, immission and soil gas concentration measurements. Appl Geochem 2014;49:218-24.
45. Meneses M, Schuhmacher M, Domingo JL. Health risk assessment of emissions of dioxins and furans from a municipal waste incinerator: comparison with other emission sources. Environ Int 2004;30(4):481-89.
46. Morra P, Lisi R, Spadoni G, Maschio G. The assessment of human health impact cau-

sed by industrial and civil activities in the Pace Valley of Messina. Sci Total Environ 2009;407(12):3712-20.

47. Morselli L, Passarini F, Piccari L, Vassura I, Bernardi E. Risk assessment applied to air emissions from a medium-sized Italian MSW incinerator. Waste Manag Res 2011;29(10) Suppl:48-56.
48. Nakazawa K, Nagafuchi O, Kawakami T, et al. Human health risk assessment of mercury vapor around artisanal small-scale gold mining area, Palu city, Central Sulawesi, Indonesia. Ecotoxicol Environ Saf 2016;124:155-62.
49. Nawab J, Li G, Khan S, et al. Health risk assessment from contaminated foodstuffs: a field study in chromite mining-affected areas northern Pakistan. Environ Sci Pollut Res Int 2016;23(12):12227-36.
50. Naz A, Mishra BK, Gupta SK. Human Health Risk Assessment of Chromium in Drinking Water: A Case Study of Sukinda Chromite Mine, Odisha, India. Exposure and Health 2016;8(2):253-64.
51. Neves O, Abreu MM. Are uranium-contaminated soil and irrigation water a risk for human vegetables consumers? A study case with Solanum tuberosum L., Phaseolus vulgaris L. and Lactuca sativa L. Ecotoxicology 2009;18(8):1130-36.
52. Noli F, Tsamos P. Concentration of heavy metals and trace elements in soils, waters and vegetables and assessment of health risk in the vicinity of a lignite-fired power plant. Sci Total Environ 2016;563-564:377-85.
53. Obiri S, Dodoo DK, Okai-Sam F, Essumang DK. Non-cancer health risk assessment from exposure to cyanide by resident adults from the mining operations of Bogoso Gold Limited in Ghana. Environ Monit Assess 2006;118(1-3):51-63.
54. Ollson CA, Knopper LD, Whitfield Aslund ML, Jayasinghe R. Site specific risk assessment of an energy-from-waste thermal treatment facility in Durham Region, Ontario, Canada. Part A: Human health risk assessment. Sci Total Environ 2014;466-467:345-56.
55. Ordonez A, Alvarez R, Charlesworth S, De Miguel E, Loredo J. Risk assessment of soils contaminated by mercury mining, Northern Spain. J Environ Monit 2011;13(1):128-36.
56. Orisakwe OE, Dagur EA, Mbagwu HO, Udowelle NA. Lead Levels in Vegetables from Artisanal Mining Sites of Dilimi River, Bukuru and Barkin Ladi North Central Nigeria: Cancer and Non-Cancer Risk Assessment. Asian Pac J Cancer Prev 2017;18(3):621-27.
57. Paladino O, Massabo M. Health risk assessment as an approach to manage an old landfill and to propose integrated solid waste treatment: A case study in Italy. Waste Manag 2017;68:344-54.
58. Pelfrene A, Detriche S, Douay F. Combining spatial distribution with oral bioaccessibility of metals in smelter-impacted soils: implications for human health risk assessment. Environ Geochem Health 2015;37(1):49-62.
59. Perez-Maldonado IN, Ochoa Martinez AC, Ruiz-Vera T, Orta-Garcia ST, Varela-Silva JA. Human Health Risks Assessment Associated with Polychlorinated Biphenyls (PCBs) in Soil from Different Contaminated Areas of Mexico. Bull Environ Contam Toxicol 2017;99(3):338-43.
60. Perrodin Y, Donguy G, Emmanuel E, Winiarski T. Health risk assessment linked to filling coastal quarries with treated dredged seaport sediments. Sci Total Environ 2014;485-486:387-95.
61. Picado F, Mendoza A, Cuadra S, Barmen G, Jakobsson K, Bengtsson G. Ecological, groundwater, and human health risk assessment in a mining region of Nicaragua. Risk Anal 2010;30(6):916-33.
62. Qu C, Sun K, Wang S, Huang L, Bi J. Monte Carlo Simulation-Based Health Risk Assessment of Heavy Metal Soil Pollution: A Case Study in the Qixia Mining Area, China. Hum Ecol Risk Assess 2012;18(4):733-50.
63. Ramirez N, Cuadras A, Rovira E, Borrull F, Marce RM. Chronic risk assessment of exposure to volatile organic compounds in the atmosphere near the largest Mediterranean industrial site. Environ Int 2012;39(1):200-09.
64. Rapant S, Dietzova Z, Cicmanova S. Environmental and health risk assessment in abandoned mining area, Zlata Idka, Slovakia. Environ Geol 2006;51(3):387-97.
65. Roberts RJ, Chen M. Waste incineration - how big is the health risk? A quantitative method to allow comparison with other health risks. J Public Health (Oxf) 2006;28(3):261-66.
66. Rovira J, Mari M, Nadal M, Schuhmacher M, Domingo JL. Partial replacement of fossil fuel in a cement plant: risk assessment for the population living in the neighborhood. Sci Total Environ 2010;408(22):5372-80.
67. Rovira J, Nadal M, Schuhmacher M, Domingo JL. Environmental levels of PCDD/Fs and metals around a cement plant in Catalonia, Spain, before and after alternative fuel implementation. Assessment of human health risks. Sci Total Environ 2014;485-486:121-29.
68. Ruffle B, Henderson J, Murphy-Hagan C, Kirkwood G, Wolf F, Edwards DA. Application of probabilistic risk assessment: Evaluating remedial alternatives at the Portland Harbor Superfund Site, Portland, Oregon, USA. Integr Environ Assess Manag 2018;14(1):63-78.
69. Sanchez-Soberon F, Rovira J, Mari M, et al. Main components and human health risks assessment of PM10, PM2.5, and PM1 in two areas influenced by cement plants. Atmos Environ 2015;120:109-16.
70. Sanusi MSM, Ramli AT, Hassan WMSW, et al. Assessment of impact of urbanisation on background radiation exposure and human health risk estimation in Kuala Lumpur, Malaysia. Environ Int 2017;104:91-101.
71. Schuhmacher M, Domingo JL, Garreta J. Pollutants emitted by a cement plant: health risks for the population living in the neighborhood. Environ Res 2004;95(2):198-206.
72. Shi GL, Lou LQ, Zhang S, Xia XW, Cai QS. Arsenic, copper, and zinc contamination in soil and wheat during coal mining, with assessment of health risks for the inhabitants of Huaibei, China. Environ Sci Pollut Res Int 2013;20(12):8435-45.
73. Sipter E, Rozsa E, Gruiz K, Tatrai E, Morvai V. Site-specific risk assessment in contaminated vegetable gardens. Chemosphere 2008;71(7):1301-07.
74. Swati, Ghosh P, Thakur IS. An integrated approach to study the risk from landfill soil of Delhi: Chemical analyses, in vitro assays and human risk assessment. Ecotoxicol Environ Saf 2017;143:120-28.
75. Taiwo AM, Awomeso JA. Assessment of trace metal concentration and health risk of artisanal gold mining activities in Ijeshaland, Osun State Nigeria- Part 1. J Geochem Explor 2017;177:1-10.
76. Tarafdar A, Sinha A. Public health risk assessment with bioaccessibility considerations for soil PAHs at oil refinery vicinity areas in India. Sci Total Environ 2018;616-617:1477-84.
77. Tong R, Yang X, Su H, et al. Levels, sources and probabilistic health risks of polycyclic aromatic hydrocarbons in the agricultural soils from sites neighboring suburban industries in Shanghai. Sci Total Environ 2018;616-617:1365-73.
78. Uddh-Soderberg TE, Gunnarsson SJ, Hogmalm KJ, Lindegard MI, Augustsson AL. An assessment of health risks associated with arsenic exposure via consumption of homegrown vegetables near contaminated glassworks sites. Sci Total Environ 2015;536:189-97.
79. Ugwu KE, Ukoha PO. Polycyclic aromatic hydrocarbons (PAHs) in surface sediments near a mining site in Okobo-Enjema, Nigeria: concentrations, source apportionment and risk assessment. Environ Geochem Health 2018;40(1):359-73.
80. Vilavert L, Nadal M, Schuhmacher M, Domingo JL. Long-term monitoring of dioxins and furans near a municipal solid waste incinerator: human health risks. Waste Manag Res 2012;30(9):908-16.
81. Wang J, Zhang X, Ling W, et al. Contamination and health risk assessment of PAHs in soils and crops in industrial areas of the Yangtze River Delta region, China. Chemosphere 2017;168:976-87.
82. Wang Y, Wang R, Fan L, et al. Assessment of multiple exposure to chemical elements and health risks among residents near Huodehong lead-zinc mining area in Yunnan, Southwest China. Chemosphere 2017;174:613-27.
83. Wcislo E, Bronder J, Bubak A, Rodriguez-Valdes E, Gallego JLR. Human health risk assessment in restoring safe and productive use of abandoned contaminated sites. Environ Int 2016;94:436-48.
84. Wcislo E, Ioven D, Kucharski R, Szdzuj J. Human health risk assessment case study: an abandoned metal smelter site in Poland. Chemosphere 2002;47(5):507-15.
85. Wei J, Chen M, Song J, et al. Assessment of Human Health Risk for an Area Impacted by a Large-Scale Metallurgical Refinery Complex in Hunan, China. Hum Ecol Risk Assess 2015;21(4):863-81.
86. Xu B, Xu Q, Liang C, Li L, Jiang L. Occurrence and health risk assessment of trace heavy metals via groundwater in Shizhuyuan Polymetallic Mine in Chenzhou City, China. Frontiers of Environmental Science & Engineering 2015;9(3):482-93.
87. Yang J, Kim EC, Shin DC, Jo SJ, Lim YW. Human exposure and risk assessment of cadmium for residents of abandoned metal mine areas in Korea. Environ Geochem Health 2015;37(2):321-32.
88. Yang J, Chen T, Lu L, Tang Y. In Vitro Health Risk Assessment of Ingesting Metal-Enriched Soils and Dusts in a Chinese Mining City. Hum Ecol Risk Assess 2015;21(8):2005-21.
89. Yang Q, Chen H, Li B. Source identification and health risk assessment of metals in indoor dust in the vicinity of phosphorus mining, Guizhou Province, China. Arch Environ Contam Toxicol 2015;68(1):20-30.
90. Zakharova T, Tatano F, Menshikov V. Health cancer risk assessment for arsenic exposure in potentially contaminated areas by fertilizer plants: a possible regulatory approach applied to a case study in Moscow region-Russia. Regul Toxicol Pharmacol 2002;36(1):22-33.
91. Zeng D, Zhou S, Ren B, Chen T. Bioaccumulation of Antimony and Arsenic in Vegetables and Health Risk Assessment in the Superlarge Antimony-Mining Area, China. J Anal Methods Chem 2015;2015:909724.
92. Zhuang P, Lu H, Li Z, Zou B, McBride MB. Multiple exposure and effects assessment of heavy metals in the population near mining area in South China. PLoS One 2014;9(4):e94484.