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Original article

Approach to Chemical Health Risk Assessment for Maintenance Workers at Electronics Manufacturing Facilities

Kyong-Hui Lee [1], Sangjun Choi [2,3,☆], Kyung Ehi Zoh [4,5], Dong-Hee Koh [6], Won Kim [7], Dong-Uk Park [8,*]

[1] US Army 65th Medical Brigade, Force Health Protection and Preventive Medicine Unit, Republic of Korea
[2] Graduate School of Public Health and Healthcare Management, The Catholic University of Korea, Seoul, Republic of Korea
[3] Catholic Institute for Public Health and Healthcare Management, Seoul 06591, Republic of Korea
[4] Department of Environmental Health, Graduate School of Public Health, Seoul National University, Seoul, Republic of Korea
[5] National Cancer Control Institute, National Cancer Center, Goyang, 10408, Republic of Korea
[6] Department of Occupational and Environmental Medicine, Severance Hospital, Yonsei University, Seoul, Republic of Korea
[7] Wonjin Institute for Occupational and Environmental Health, Seoul, Republic of Korea
[8] Department of Environmental Health, Korea National Open University, Seoul, Republic of Korea

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A B S T R A C T

Background: Maintenance workers in the electronics manufacturing industry are exposed to a diverse combination of gaseous and particulate substances, yet specific guidance for assessing their chemical health risks remains limited. The aims of this study are to develop a stepwise framework approach for qualitatively assessing hazard severity, exposure probability, and chemical health risks for maintenance workers at electronic manufacturing facilities, and to propose a method for categorizing these factors through occupational health risk assessment (OHRA).

Methods: We developed a stepwise framework for qualitatively assessing the health risks posed by chemicals to maintenance workers in electronics facilities. This framework employs a semiquantitative approach using ordinal scores to evaluate the severity of chemical hazards and the likelihood of exposure, particularly in situations where representative measurement data for multiple chemicals are unavailable.

Results: The framework assesses hazard severity qualitatively by considering the number of chemicals and the presence of carcinogenic, mutagenic, or reprotoxic substances or sensitizing hazards. A qualitative approach to estimating the likelihood of exposure is recommended, focusing on the effectiveness of engineering controls, the frequency and duration of maintenance works and tasks (MW), and the use of air jets. Two examples of a qualitative chemical OHRA for maintenance workers are given, one for a moderate hazard chemical integrating several exposure factors, and the second for MW on an ion implanter.

Conclusion: Further research is needed to validate this method and to develop additional practical guidance for the assessment of chemical health risks associated with MW.

Kyong-Hui Lee: https://orcid.org/0000-0001-6709-0280; Sangjun Choi: https://orcid.org/0000-0001-8787-7216; Kyung Ehi Zoh: https://orcid.org/0000-0002-2821-070X; Dong-Hee Koh: https://orcid.org/0000-0002-2868-4411; Won Kim: https://orcid.org/0000-0003-1808-6677; Dong-Uk Park: https://orcid.org/0000-0003-3847-7392

* Corresponding author. Department of Environmental Health, Korea National Open University, 86 Daehak-ro, Jongno-gu, Seoul, 03087, Republic of Korea.
E-mail address: pdw545@gmail.com (D.-U. Park).
☆ The authors contributed equally to this work as the first author.

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1. Introduction

Given the diversity of chemical exposures and hazard scenarios in the workplace, no universally accepted framework or disciplinary approach can comprehensively address the full scope of related health risks. Many major countries have established regulations that require employers to conduct risk assessments for hazardous agents, including chemicals. The US Occupational Safety and Health Administration (OSHA) [1], UK Control of Substances Hazardous to Health (COSHH) [2], and the Industrial Safety and Health Acts in Republic of Korea [1] all require hazards to be identified, risks to be assessed, and control measures to be implemented to protect the health and safety of workers. Although the foundational principles of occupational health risk assessment (OHRA) are well documented, there is a noticeable absence of specific methodologies tailored for particular operational processes or job types.

Most OHRAs conducted in the manufacturing sector—including the electronics industry—primarily focus on process operators who are exposed to individual chemicals, despite the limited number of such studies available [3,4]. Maintenance workers, however, frequently experience intermittent, high-intensity exposures to complex mixtures of dusts, gases, and solvents—scenarios that are difficult to assess accurately, especially given the limited toxicological data and lack of established occupational exposure limits (OELs) for many of these substances. While OHRAs are typically developed for operators and other frontline workers, they are not specifically tailored to the unique and varied exposures encountered by maintenance workers [3,4]. Although qualitative risk matrices and advanced quantitative methods (e.g., Monte Carlo simulation [5] and fuzzy Analytic Hierarchy Process (AHP) have been applied elsewhere [6,7], no practical framework exists for evaluating multichemical exposures across diverse maintenance tasks, including electronics maintenance operations. Nontraditional approaches like control banding—especially for nanomaterials—underscore the need for group-based methods to address hazards from rapidly evolving technologies [8]. To fill this gap, we drew on variables from our previous semiconductor-fab study to develop a framework that assesses chemical hazard severity, exposure likelihood, and overall health risk—thereby improving OHRA accessibility for maintenance workers in fab facilities [9].

Based on the variables of our previous fabrication maintenance risk assessment, this study has developed a qualitative OHRA framework with practical examples to evaluate the severity of combined exposure hazards and exposure likelihood, as well as overall chemical health risk in electronics maintenance workers. The framework we present here fills a guidance gap that may be encountered in various occupational settings by providing a practical method for assessing multiple chemical exposures in maintenance operations.

2. Methods

2.1. The range and extent of the study

This study focused on developing guidance on chemical OHRA specifically for maintenance works (MW) in electronic product manufacturing plants. The main focus of this study is to: 1) Address the chemical hazards faced by MW, who are often exposed to multiple and intermittent chemical agents during maintenance operations in electronics manufacturing processes; 2) Develop a stepwise framework for assessing chemical health risks in MW in electronics manufacturing and for distinguishing hazard severity based on the number of chemicals involved; and 3) Propose an approach for estimating the severity of chemical hazards, the likelihood of exposure, and overall health risks associated with maintenance activities. Factors for qualitative OHRA, along with example approaches, are subjectively proposed based on the assumption that maintenance workers are exposed to multiple chemicals during electronic equipment maintenance. Semi-qualitative assessments of hazard severity and exposure likelihood—based on ordinal scores (Tables 1 and 2) and semi-qualitative criteria (Table 3)—are ultimately suggested to be structured into qualitative classifications: low, moderate, and high. The total ordinal score, estimated from the classification of hazard severity and exposure likelihood, is recommended to be divided into three categories using tertile-based classification. Alternatively, it can be divided into four categories using quartile-based classification. However, the selection and scoring of assessment factors may vary among evaluators, underscoring the need for consistency and a sound scientific rationale. The three-level, semi-qualitative classification presented as an example (high, moderate, or low) is inherently influenced by subjective factors, such as the evaluator's judgment, the chemical properties and the specific exposure conditions in maintenance settings where health risk assessments are conducted. The classification of chemical severity (Fig. 1) and exposure likelihood (Fig. 2) is based on the toxicity and exposure-related characteristics of chemicals encountered or used during MW. This study recommends a qualitative risk assessment approach, with an emphasis on evaluating chemical severity and exposure likelihood using a semi-quantitative classification system based on ordinal scoring (Tables 1 and 2). The qualitative risk assessment approach includes semi-qualitative methods, which

Table 1
Key factors to consider when assessing the hazards of chemicals generated during the maintenance of electronic product manufacturing equipment, with a semi-qualitative assessment based on ordinal scoring criteria

Factors*	Example of how to categorize semi-quantitative score†
The existence of combined multiple exposures	Yes (2), No (1)
The existence of synergistic due to combined exposure	Yes (2), No (1)
The existence of additive effects due to combined exposure	Yes (2), No (1)
Exposure to multiple chemicals containing CMR risks	Yes (2, or the highest hazard category, regardless of the severity of other hazards), No (1)
Exposure to multiple chemicals containing sensitizers	Yes (2, or the highest hazard category, in the absence of CMR substances), No (1)
Exposure to chemicals with a low level of threshold limit values	Yes (2), No (1)
Total	Example of hazard severity categorization by multiplying the overall ordinal scale (64). The total ordinal score (64) is divided into three categories using tertile-based classification.: high; >44, moderate; 22-43, low: <22

CMR, carcinogen, mutagenic and reprotoxic.

* Hazard categories can be determined based on either the total score or only the presence of a factor that can be consistently determined by the evaluator.

† Scores and number of category can be raised or lowered by the evaluator.

Table 2
Key factors for assessing the likelihood of exposure to chemicals that maintenance workers may encounter during equipment MW for electronics manufacturing process, with a semi-qualitative assessment based on ordinal scoring criteria

Factors*	Example of how to categorize semi-quantitative score†
Using well-operated LEV during MW	Yes (2), No (1)
• No LEV installed • An inefficient LEV system in place	Yes (4, or classified at the highest level, irrespective of exposure status or conditions) Yes (3)
Frequent air-jet use	Yes (2), No (1)
• Frequent use of air-jet devices without proper connection to designated cleaning systems	Yes (4)
Frequency of MW	Daily (4), Weekly (2), Monthly (1)
The average duration of MW (hr/frequency)	>4 hours (4), 2-4 hours (2), <1 hour (1)
Location of MW performed	Semi-confined and confined spaces (2), and open space (1)
Total	Example of exposure likelihood categorization by multiplying the overall ordinal scale (512). The total ordinal score is divided into three categories using tertile -based classification.: high; >341, moderate; 171-341, low: <171

LEV, local exhaust ventilation, MW, maintenance work.
* Exposure categories can be determined based on either the total score or only the presence of a factor that can be consistently determined by the evaluator.
† Scores and number of category can be raised or lowered by the evaluator.

Table 3
Example of a qualitative factors* for chemical hazard and exposure assessment for workers performing maintenance work in a semiconductor process facility, based on semi-qualitative classification categories

Type of assessment	High category	Moderate category	Low category
Hazard assessment	• High acute toxicity due to corrosive properties • Sensitizing potential even at low exposure levels • Exposure to any CMRs • Exposure to multiple chemicals with synergistic or additive health effects • Exposure to fumes containing heavy metals • High neurotoxic potential, even at low levels of exposure	• Exposure to multiple chemicals with no CMR or combined health effects • Multiple chemicals (most process facilities)	• Exposure to irritants • Exposure to single chemical with no CMR or combined health effects
Exposure assessment	• Always use air blast to remove trapped dust • No or poor capability with local exhaust ventilation • Frequent MW, every day • Requires long MW duration, more than one hour per MW • Concentration always above OEL†	• Provision of local exhaust ventilation combined with medium efficiency cleaners • Frequent use of air blast to remove trapped dust • Moderate capacity of local exhaust • MW performed infrequently, every week • MW duration required, less than two hours per MW • Concentration often above OEL†	• Provision of local exhaust ventilation linked to high efficiency cleaners • No or infrequent use of air blast to remove entrapped dust • Rarely performed MW, once per month • Short MW duration, a few minutes per task • Low concentration level, always below OEL†

CMR, carcinogenic, mutagenic, or reprotoxic; MW, maintenance work; OEL, occupational exposure limit.
* Chemical hazard and exposure categories can be determined based on either the total score or only the presence of a factor that can be consistently determined by the evaluator. The evaluator is responsible for selecting the factors and determining the level of classification.
† If exposure measurement data available.

incorporate both qualitative judgments and structured scoring systems. This study excludes OHRA related to the cleaning of disassembled parts and machinery within process facilities, as well as risks from agents other than chemicals.

2.2. Chemical hazard assessment for MW

The key factors for assessing the hazard severity of multiple chemicals generated during equipment maintenance in electronics manufacturing are suggested below (Table 1). These include a qualitative classification example based on critical indicators of chemical severity—such as the presence of multiple chemical exposures with synergistic or additive toxic effects [9], the inclusion of carcinogenic, mutagenic, or reprotoxic (CMR) substances, and the potential for sensitization. Toxicological and human data should be considered sufficient when comprehensive, high-quality information on toxicity and exposure effects is available from literature reviews and safety data sheets (SDSs), in accordance with the Globally Harmonized System (GHS) for hazard assessment. In this study, the severity of chemical hazards is proposed to be categorized based on the presence of CMR substances, sensitization potential, and the combined effects of multiple chemicals with synergistic or additive interactions, although this classification may vary among assessors. If a CMR substance is present among multiple chemicals, the overall chemical hazard severity can be classified in the highest hazard category, regardless of the total score or the severity of other individual hazards. Similarly, if a sensitizing substance is present in the absence of any CMRs, the overall hazard severity may also be classified in the highest hazard category (Tables 2 and 3).

2.3. Chemical exposure assessment for MW

A stepwise, qualitative framework is proposed based on the assumption that maintenance workers are exposed to multiple chemicals during the maintenance of electronic equipment in manufacturing facilities, and that exposure measurement data are not available (Fig. 2). This framework incorporates key factors for

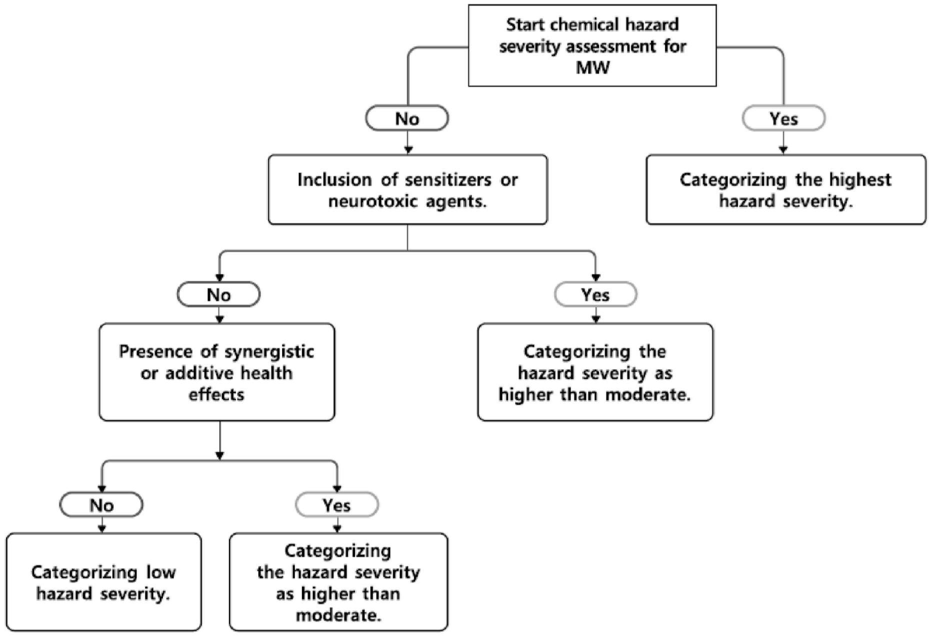

Fig. 1. Stepwise framework for assessing chemical hazard severity: qualitative and semi-qualitative approaches. CMR, carcinogens, mutagens and reproductive toxins; MW, maintenance work or task.

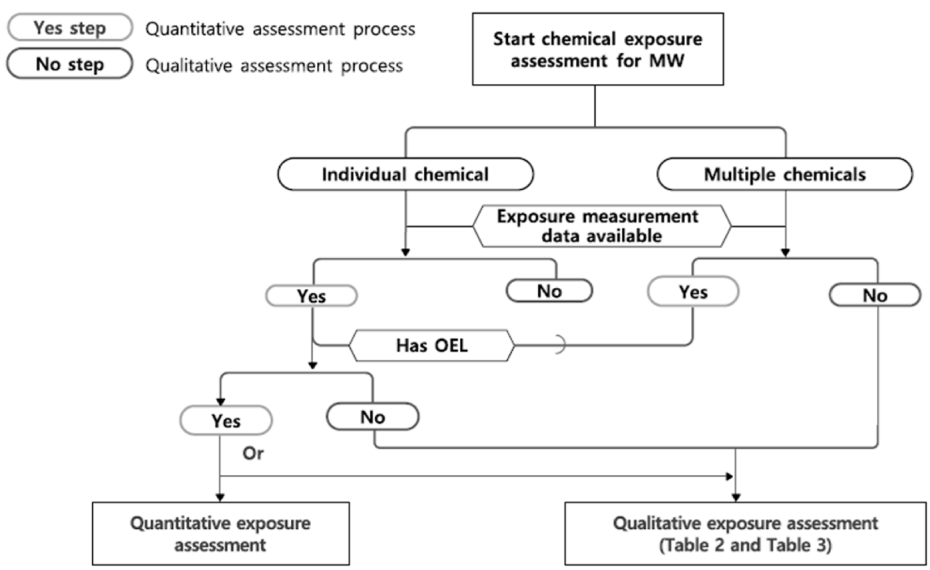

Fig. 2. Stepwise framework for assessing combined chemical exposure: integration of qualitative, semi-qualitative and quantitative approaches. MW, maintenance work or task; OEL, occupational exposure limit.

assessing the likelihood of such exposures, supported by qualitative or semi-qualitative evaluations using ordinal scale points (Table 2) and semi-qualitative criteria (Table 3). The availability of quantitative exposure measurement data representing the level of exposure. Depending on the availability of representative multiple exposure measurements, the exposure likelihood can be classified using either ordinal point values (Table 2) or semi-qualitative categories (Table 3). The use of air-jets for equipment cleaning—including their frequency and duration—along with maintenance frequency, duration, and the presence of local exhaust ventilation (LEV), including portable exhaust ducts connected to cleaners, are recommended for assessment using either ordinal scores or qualitative classification. If LEV is not installed during maintenance work (MW), the exposure category can be classified at the highest level, irrespective of exposure status or conditions. Guidelines for assessing the risk of chemical spills or accidental releases and the likelihood of unplanned releases or spills during maintenance were excluded.

2.4. An approach to chemical hazard, exposure, and OHRA

As one of the approaches for chemical OHRA, we propose a qualitative chemical OHRA for MW that assumes that they are exposed to multiple chemicals generated during equipment maintenance in electronic manufacturing facilities, semiconductor process facilities, and ion implanter maintenance, as well as to chemicals with moderate hazard classification. It is suggested that the overall health risk be determined by combining the three-category classifications of hazard severity and exposure probability, resulting in risk levels of low, moderate, or high. This OHRA approach is designed based on conditions assumed for MW in electronic process facilities, with a particular focus on semiconductor processes. However, the number of categories may vary depending on the assessor.

3. Results

An example of a qualitative classification of hazard severity and exposure probability—along with the corresponding classification of chemical health risks and recommended control measures—is presented, based on assumed typical maintenance scenarios for semiconductor process facilities (Table 4). Chemical health risk levels (low, moderate or high) are categorized by considering chemical properties such as the presence of CMR substances, synergistic effects, and exposure-related factors including ventilation efficiency, air blast usage, and maintenance frequency.

Given that obtaining quantitative exposure data is often impractical for sporadic or irregular maintenance activities, this study recommends estimating the likelihood of chemical exposure based on the level of engineering controls, the use of air blasting, and maintenance characteristics such as task frequency and duration. Maintenance workers who frequently perform tasks involving air blasting for four hours or more are generally exposed to multiple hazardous chemical agents and, even in the absence of quantitative data, their exposure can be qualitatively assessed as greater than moderate.

As an example, a qualitative chemical health risk is proposed for a substance classified as having moderate hazard severity. When this is combined with varying levels of engineering controls and multiple exposure-related MW characteristics, the overall chemical health risk may be classified as high—ranging from moderate to high depending on the specific exposure conditions (Table 5). In addition, to demonstrate a practical approach, a qualitative chemical OHRA is also proposed for maintenance workers involved in the maintenance of ion implanters under semiconductor operations (Table 6). The chemical health risks for maintenance workers handling ion implanters were classified as "high," based on the combination of the highest hazard rating for carcinogenic chemicals such as arsenic and a moderate probability of exposure, considering factors such as the effectiveness of engineering control measures, etc.

4. Discussion

This study proposes qualitative approaches for assessing chemical hazards, exposures, and health risks tailored to maintenance workers in electronic process equipment. When conducting OHRA as mandated by various regulations, employers face significant challenges, including selecting relevant hazard and exposure factors, conducting quantitative or qualitative evaluations, and ensuring compliance with complex regulatory requirements. These challenges are particularly significant for Small and Medium-sized Enterprises (SMEs) due to their limited resources, insufficient technical expertise, and restricted access to reliable exposure data. These difficulties are further intensified for maintenance workers in a variety of process facilities, including electronics manufacturing, as they carry out a range of specific tasks involving intermittent exposure to hazards [10]. The variability and inaccessibility of these tasks hinder the collection of representative data [11], and are further complicated by the lack of standardized sampling methods, established occupational exposure limits (OELs), and consistent regulatory frameworks. This study discusses the key characteristics

Table 4
Example of qualitative control level and methods* based on hazard and exposure for chemicals used in maintenance tasks in a semiconductor process facility

Qualitative classification of chemical health risks	Hazard level and characteristics	Exposure level and characteristics	Control level and methods for chemical health risk reduction
Low	• Low hazard • Only single or multiple irritant chemicals or high OEL hazardous substances	• Low exposure • Small amounts of high OEL cleaning chemicals • No use of cleaning chemicals • No use of air blast to remove particles trapped in equipment • Infrequent and less than 1 hour per month MW • Well controlled ventilation system	• Maintain good work practices, including the use of PPE
Moderate	• Low or moderate hazard • Only single or multiple chemicals with possible neurotoxic or corrosive effects or allergic reactions with prolonged exposure • Only single or multiple chemicals containing dermal absorption	• Moderate exposure • Routine use of high volatility cleaning chemicals for maintenance purposes • Use of air blast to remove particles trapped in equipment • Frequent maintenance of more than 1 hour per week • Poorly controlled LEV system	• Maintain good work practices, including the use of PPE • Use air blast when removing trapped particles and cleaning with local ventilation system connected to scrubber cleaners • Conduct periodic exposure assessments
High	• Moderate or high hazard • Only single or multiple chemicals containing any potential CMR effects	• Moderate or high exposure • Routine use of large quantities of highly volatile cleaning chemicals for maintenance purposes • Frequent use of air blast to remove particles trapped in equipment • Frequent maintenance of more than 1 hour per day • No controlled LEV system during maintenance • Maintenance in confined or semi-enclosed spaces • No use of appropriate respirators	• Follow good work practices, including the use of PPE • Use air blast when removing entrapped particles and cleaning with local exhaust ventilation connected to scrubber cleaners • Conduct periodic exposure assessments Conduct periodic special medical examinations

LEV, local exhaust ventilation; MW, maintenance work; OEL, occupational exposure limit; PPE, personal protective equipment.
* Level of hazard, exposure, health risk and control may be increased or decreased by the evaluator.

Table 5
Example of a qualitative chemical health risk assessment for a chemical with a moderate hazard class combined with several engineering level and MW characteristics

MW activities related to the level of chemical exposure	Classification	Chemical agents with moderate hazard class*		
		Low	Moderate*	High
Availability of exposure measurement data	Yes	Proceed to the quantitative OHRA process that is addressed in section 5.6.		
	No	Qualitative OHRA on the basis of the evaluation of the factors in the column below this table		
Effectiveness of local exhaust ventilation	No			
	Low			
	Moderate		Yes	
	High			
Use of air-jet	No use			
	Without scrubber		Yes	
	With scrubber			
Frequency of use of air-jet per maintenance task	No use			
	<5 times: low			
	5-10 times: moderate		Yes	
	>10 times: high			
Use of a chemical cleaning agent	No use			
	Yes		Yes	
Amount of chemical agent used in the MW (ml per task)	No use			
	<500 ml: low			
	500-1000 ml: moderate		Yes	
	>1000 ml: high			
Frequency of chemical agent used for MW	No use			
	<5 times: low			
	5-10 times: moderate			
	>10 times: high		Yes	
Openness of the MW space	Open without confined space		Yes	
	Semi-confined space			
	Confined space			
Use of appropriate PPE, including respirators	Yes		Yes	
	No			
Total qualitative chemical exposure level†			Greater than high	

LEV, local exhaust ventilation; LEV, local exhaust ventilation; OEL, occupational exposure limit; OHRA, occupational health risk assessment; PPE, personal protective equipment.
* Can be grouped into cleaners, particulates, dusts, fumes, VOCs, and specific chemicals to which maintenance workers may be exposed. Hazard severity is assumed to be "moderate".
† Based on the combination of hazard severity group and exposure level using the health risk ranking matrix with the appropriate category number.

of MW in electronic process facilities, aiming to support the development of a practical OHRA framework and to justify the use of a qualitative approach.

Firstly, the specific characteristics of MW carried out in semi-confined or confined spaces within electronic process facilities, which often result in sporadic but intense exposure to various health hazards, including chemicals, should be carefully considered. This contrasts sharply with the characteristics of production workers, who are continuously engaged in operational activities and experience relatively more predictable and consistent exposure patterns. Guidance from the European Chemicals Agency (ECHA) [12] and UK Health and Safety Executive (HSE) [2] provides methodologies for prioritizing urgent risks that are primarily tailored to process operators working under the assumption of single chemical exposures. However, these approaches are not well suited to the case of maintenance workers, who are typically exposed to multiple chemical agents, making it difficult to assess such simultaneous exposures. [4]. During maintenance tasks in electronics manufacturing facilities, such as cleaning, repairing or replacing equipment, workers may be temporarily exposed to a variety of chemicals, including solvents, acids and alkalis, as well as by-products, gases, and aerosol particles used or generated

Table 6
Example of a qualitative chemical health risk assessment for maintenance workers involved in the maintenance of ion implanters

Type of assessment	Identification and evaluation (semi-quantitative score†)	Level of category*
Hazard assessment	• Exposure to multiple chemicals, including arsenic compounds, ion impurities, fine particles Inclusion of CMR and sensitizers among the multiple chemicals	High (Tables 1 and 4)
Exposure assessment	• Insufficient measured data available to characterize the exposure of maintenance workers to multiple chemicals. • Using a well-operated local exhaust ventilation system connected to a scrubber (2 out of 4) • Frequent use of air blasting to remove entrapped dust by blowing it away, without connecting it to scrubbers (4 out of 4) • Frequent MW, daily (4 out of 4) • >4 hours MW per ion implanter x 2 ion implanters/day (4 out of 4) • MW in enclosed or semi-enclosed area (2 out of 2) • Multiple total score = 256 out of 512(From Table 2)†	Moderate (Tables 2 and 4)
Chemical health risk assessment	• High hazard and moderate exposure	High health risk

CMR, carcinogenic, mutagenic, or reprotoxic; MW, maintenance work.
* The qualitative classification or number of hazard and exposure categories may be based on the total score or only on the presence of a factor that can be consistently determined by the assessor. Three categories (low, moderate, and high) have been suggested in this table.
† Evaluation factors and scores by factor can be increased by the evaluator.

during operations. Maintenance tasks often require working in different areas under varying conditions [13], making it difficult to accurately predict and measure exposure levels due to the dynamic and variable nature of the work [14], especially at SMEs. To overcome the difficulties in standardizing assessments due to the varying duration, frequency, and intensity of exposure during maintenance tasks, qualitative assessments of chemical health risks may be more efficient for MW, as their specific work and job characteristics differ from other roles, such as those of operators, making quantitative assessments less practical (Table 3).

Secondly, when assessing the severity of multiple chemical hazards, including CMR, it is recommended that the highest hazard level of the chemicals to which the maintenance workers are exposed be considered (Fig. 1). Each chemical has unique hazards, complicating the process of comprehensively assessing and managing risk [15]. Chemical hazards are typically categorized based on toxicity information derived from sources such as the Globally Harmonized System (GHS) risk (R) and hazard (H) codes and CMR classifications. For example, the Clean Electronics Production Network (CEPN) categorizes the health effects of chemicals into five levels based on GHS SDS information, with chemicals classified as CMR and skin and respiratory sensitizers at the highest hazard category [16]. Most maintenance workers in semiconductor facilities, particularly those involved in processes such as ion implantation, photolithography, diffusion, metal deposition and etching, are exposed to multiple chemical hazards. These hazards include fine particles and CMR substances, which can be assessed as posing a high hazard category. This study recommends assigning the highest hazard severity when a CMR is present, when a sensitizer is present without a CMR, or when synergistic effects are anticipated, regardless of other hazard scores (Tables 1, 4 and 6).

Thirdly, we also recommend that the qualitative likelihood of chemical exposure can be assessed based on a combination of factors, including the level of engineering control, the frequency of maintenance tasks, and the duration of each task (Tables 3 and 4) [10,11]. In the absence of quantitative exposure measurement data, exposure to multiple chemicals and dusts can be estimated qualitatively by considering categorical variables such as the types and quantities of chemicals used, the duration and frequency of the tasks, and the effectiveness of ventilation systems [17]. (Tables 3 and 5). When a sufficient number of chemical exposure data points are available to represent the exposure profile of a group of maintenance workers, the distribution of these exposures—along with metrics such as the 95th percentile—can be compared to the occupational exposure limit (OEL). Based on this comparison, exposure levels can be qualitatively categorized [10] as low (when the 95% confidence interval is below the OEL), moderate (when it falls within the 95% confidence interval), or high (when the 95th percentile exceeds the OEL [18]) (Fig. 2). However, quantitative exposure assessment for maintenance workers is inherently challenging due to the irregular, sporadic, or unplanned nature of their tasks, and their frequent involvement with multiple chemical agents. These conditions are typical of most workplaces, including electronic process facilities. Our proposals are similar to the qualitative exposure assessment reported by CEPN, which is based on a combination of the vapor pressure of maintenance chemicals (such as cleaning agents), level of engineering measures, and the frequency of maintenance operations [16]. To improve qualitative exposure assessments, detailed task analyses should be conducted to identify potential exposure points and collect qualitative data through worker interviews and observations [12].

Fourthly, we proposed a qualitative chemical OHRA and a scenario assuming intermittent exposure to several moderately hazardous chemicals during maintenance (Tables 4–6). As an example, MW involving ion implanters was classified as having a 'high' chemical health risk, owing to potential exposure to carcinogenic arsenic [19] and X-rays [20], along with a moderate likelihood of exposure, given the existing engineering control measures (Table 6). Quantitative methods provide accurate, measurable data for comparison with standards and regulatory limits [5], but they require extensive resources, making them costly and impractical for maintenance workers intermittently and unexpectedly exposed to chemicals. Qualitative methods are fast, cost-effective, and practical for electronic equipment maintenance, and provide timely insights despite their lack of precision and reliance on subjective judgment. Several countries have adopted qualitative methods for assessing chemical risks to health, providing both legislative frameworks and practical guidance tailored to different industries and processes without limiting their application to specific types of work. The UK HSE has outlined these guidelines in the COSHH, which serves as both a code of practice and a source of guidance [21]. In addition, the HSE has developed simple risk assessment templates for six different industries [22]. In Germany, the Technical Rules for Hazardous Substances (TRGS: Technische Regeln für Gefahrstoffe) have introduced a guide for chemical risk assessment, including practical, industry-specific guidance, such as on health risks from hazardous substances in welding and hairdressing [21]. The number of categories and the level of categorization of hazard, likelihood of exposure, and risk of a given chemical may vary depending on the judgment of the assessor and the specific context of the assessment (Tables 3 and 4).

A key limitation of this study is that the proposed qualitative assessment approaches for occupational health risk—which are based on ordinal scoring and categorization criteria presented as examples for maintenance workers—are not supported by a clearly established empirical or theoretical framework. However, they were developed through expert discussions among coauthors ($n = 6$) with substantial experience in OHRA. The absence of formal validation—such as expert consensus procedures, inter-rater reliability testing, or pilot studies—raises concerns regarding the reproducibility and generalizability of the proposed approach. Although our OHRA framework, which focuses on qualitative analysis, has limitations in demonstrating strong methodological novelty and scientific contribution, its example-based assessments of hazard severity, exposure likelihood, and overall health risk (as shown in Tables 3–5) are designed to be adaptable to a wide range of workplace environments. Further research is needed to conduct empirical validation and strengthen the methodological robustness of the framework.

A major strength of this study lies in its development of a practical and adaptable framework for qualitative chemical OHRA that can be applied not only to maintenance work in electronics manufacturing but also to other job types involving irregular, multichemical exposures across various industrial settings. This study can also help companies, especially SME that lack risk assessment expertise, to effectively prioritize chemical health risks.

In conclusion, this study proposes qualitative chemical OHRA approaches that integrate hazard levels and exposure probabilities for multiple chemicals encountered during maintenance operations in electronic manufacturing settings. By considering the stepwise conditions typically faced by maintenance workers, the proposed framework offers a practical and adaptable tool applicable to a range of job types. Further research is needed to conduct empirical validation and strengthen the methodological robustness of the framework.

CRediT authorship contribution statement

Kyong-Hui Lee: Writing – review & editing, Investigation, Formal analysis. **Sangjun Choi:** Writing – review & editing, Visualization, Validation, Conceptualization. **Kyung Ehi Zoh:** Writing – review & editing, Visualization, Validation, Data curation. **Dong Hee Kho:** Writing – review & editing, Visualization, Validation, Methodology, Investigation. **Won Kim:** Writing – review & editing, Investigation, Conceptualization. **Dong-Uk Park:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

Generative AI tools were used to rephrase sections of the manuscript for improved clarity during its preparation. However, the authors developed and validated all scientific content, interpretation of results and conclusions. The authors take full responsibility for the content and integrity of the work.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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