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Formaldehyde exposure risk assessment among fiberboard furniture manufacturing workers in Thailand: Comparison of TIS 2012 and EPA IRIS standards

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Abstract

Formaldehyde exposure in medium-density fiberboard furniture manufacturing is an important occupational health concern because formaldehyde-containing resins can release hazardous airborne emissions during production processes. The aim of this study was to evaluate and compare formaldehyde exposure risks among furniture manufacturing workers using the Thai Industrial Standard (TIS) 2012 semi-quantitative model and the United States Environmental Protection Agency Integrated Risk Information System (EPA IRIS) quantitative model, and to examine the concordance between the two frameworks. A cross-sectional study was conducted among 439 workers from ten departments in a medium-density fiberboard furniture factory in Chachoengsao Province, Thailand. Work characteristics and health symptoms were collected using structured questionnaires. Full-shift personal air sampling was performed in accordance with the National Institute for Occupational Safety and Health Method 5700, and samples were analyzed by high-performance liquid chromatography. Risk characterization was conducted using TIS 2012 based on exposure rating × health effect rating, while EPA IRIS was applied to estimate non-cancer risk using the hazard quotient and lifetime cancer risk using the inhalation unit risk. Non-cancer and lifetime cancer risks were assessed using HQ and inhalation unit risk. The mean formaldehyde concentration was 5.47 mg/m^3 (0.70–11.55 mg/m^3), peaking in the Clearing department (11.55 mg/m^3). TIS 2012 classified 80% of departments as very high risk, compared with 50% under the EPA IRIS HQ model. The EPA IRIS model showed hazard quotients ranging from 6.59 to 87.99 and lifetime cancer risks ranging from 7.72×10^{-3} to 1.27×10^{-1}, all exceeding the acceptable cancer risk threshold of 1×10^{-6}. Concordance between the two models was 73%, with discrepancies observed in the Edging and Drilling departments. All departments had unacceptable cancer risks, indicating the need for immediate exposure-control measures. Integrating semi-quantitative and quantitative assessment frameworks is essential for comprehensive occupational risk management. Departments identified as very high risk by both models require urgent control measures and inclusion of cancer-risk assessment in routine occupational health surveillance.

Keywords: Formaldehyde, occupational exposure, risk assessment, furniture manufacturing, TIS 2012

Introduction

Furniture manufacturing is one of Thailand's major industrial sectors, employing more than 200,000 workers and generating substantial export value. Typical processes, such as sawing,

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sanding, drilling, laminating, and packing, release varying amounts of airborne contaminants, particularly wood dust and chemical emissions [1,2]. Exposure to wood dust is associated with acute nasal and respiratory irritation and chronic conditions, including occupational asthma, chronic bronchitis, decreased lung function, and nasal adenocarcinoma [3-7]. Reflecting this evidence, the International Agency for Research on Cancer classifies wood dust as a Group 1 human carcinogen [8].

Medium-density fiberboard (MDF) production poses even higher risk because urea-formaldehyde resin releases formaldehyde gas, volatile organic compounds, ultrafine particles, and reactive resins under elevated temperature and pressure [9]. Peak exposures occur during hot-pressing operations, during which both formaldehyde and fine particulates are emitted simultaneously. Studies on Eastern Thailand MDF factories reported mean formaldehyde concentrations of 2.07 ppm and wood dust levels of 7.67 mg/m^3, exceeding United States Occupational Safety and Health Administration (OSHA) [10] and Thai occupational exposure limits (OELs) (0.75 ppm; 0.92 mg/m^3) [11]. Sensitized workers may face an increased risk even at moderate exposure levels (>5 mg/m^3) [2], highlighting the need for refined exposure assessment.

Thailand's regulatory framework, including the Occupational Safety, Health and Environment Act [12] and the Thai Industrial Standard [13], primarily relies on semi-quantitative methods and compliance with occupational exposure limits. However, these approaches may inadequately capture chronic or carcinogenic risks, particularly for substances such as formaldehyde [11]. Integrating quantitative models, such as the United States Environmental Protection Agency's (EPA) Integrated Risk Information System (IRIS) hazard quotient (HQ) and excess lifetime cancer risk, can strengthen risk estimation and support decision-making regarding engineering controls and medical surveillance [12,14].

Despite this need, studies comparing semi-quantitative and quantitative occupational risk frameworks have revealed systematic differences. A study demonstrated that the EPA quantitative model consistently outperformed semi-quantitative approaches in distinguishing risk levels across industries, and that model selection significantly influenced risk classification outcomes [15]. No previous studies have directly compared the Thai Industrial Standard (TIS) 2012 chemical risk assessment [13] with international quantitative models, such as EPA IRIS [14], in Thailand's MDF or furniture sector.

This critical evidence gap limits the selection of appropriate risk assessment tools and constrains the development of data-driven occupational health policies. Given these limitations, it is essential to determine whether TIS 2012 [13] yields risk estimates comparable to those produced by internationally recognized quantitative models [14]. Accordingly, the aim of this study was to evaluate formaldehyde exposure risks among furniture manufacturing workers using the TIS 2012 semi-quantitative model and the EPA IRIS quantitative model, and to assess the concordance between the two risk assessment frameworks. This study represents one of the first systematic evaluations of Southeast Asian MDF manufacturing. This study is expected to identify potential underestimation of chronic and carcinogenic risks and strengthen the scientific basis for selecting appropriate assessment tools in Thailand's furniture industry.

Methods

Study design and population

This cross-sectional study was conducted at an MDF furniture manufacturing facility in Chachoengsao Province, Eastern Thailand, where formaldehyde-containing resins were used in the production process. The study population comprised all 439 workers, including 323 production workers exposed to formaldehyde through manufacturing processes and 116 office staff classified as non-exposed.

The sample size was calculated assuming a 3:1 ratio of exposed to non-exposed workers, with a formaldehyde contact allergy prevalence of 8% [16], a significance level of 0.05, and 80% power. The final ratio was 2.78:1, providing a statistical power of 79.1%, marginally below the target of 80% [17] due to the actual distribution of workers between exposed and non-exposed groups.

This difference was considered negligible and did not meaningfully affect statistical validity. A total population sampling approach was used to collect questionnaire data.

Data collection instruments

A structured questionnaire was administered on site at scheduled times to collect data on (1) demographics (gender, age, education); (2) work history (department, duration, work hours); (3) smoking and alcohol consumption; and (4) workplace characteristics. The questionnaire was validated by occupational medicine and hygiene experts prior to use. The participants provided information without coercion. Consent forms were signed before participation was accepted.

Personal air sampling

Full-shift formaldehyde exposure was measured using Institute of Occupational Medicine (IOM) personal samplers with 25 mm polyvinyl chloride (PVC) filters operated at 2 L/min, following the National Institute for Occupational Safety and Health (NIOSH) Method 5700. A similar exposure group (SEG)-based sampling strategy was used to represent workers with comparable job tasks, work processes, and expected formaldehyde exposure profiles. SEGs were established based on walk-through surveys, department classification, job activities, and exposure characteristics. Eleven SEGs were defined, comprising office, laminating, combination, drilling, edging, fitting, wrapping, clearing, packing, and line operations. A range of 6 to 10 personal air samples were collected from each of 10 production departments and one non-exposed office department during routine full-shift work activities, resulting in 100 personal air samples. Samples were analyzed using high-performance liquid chromatography (HPLC) at the Bureau of Occupational and Environmental Disease, Health.

TIS 2012 semi-quantitative risk assessment

The TIS 2012 semi-quantitative risk assessment method was used to classify the risk of formaldehyde exposure among workers [13]. This method estimates risk based on three main components: exposure frequency, concentration rating, and health effect severity. The final risk score was calculated by multiplying the exposure rating (ER) by the health effect rating (HER). The HER was assigned based on carcinogenicity classification, documented health effects, and median lethal concentration (LC_{50}) toxicity data. HER values ranged from level 1, indicating minimal health impact, to level 5, indicating the most severe health impact [12,18]. The ER was calculated from the concentration rating (CR) and exposure frequency (EF). The CR was derived by comparing the measured departmental formaldehyde concentration with the permissible exposure limit/occupational exposure limit (PEL/OEL) of 0.75 ppm, equivalent to 0.92 mg/m^3 [10,11]. The EF was determined from workers' work schedules and exposure duration (ED). The final risk score was categorized into five levels: acceptable (1–3), low (4–9), moderate (10–16), high (17–20), and very high (21–25). This approach allowed department-specific classification of formaldehyde exposure risk and provided a standardized basis for comparison with the quantitative United States Environmental Protection Agency Integrated Risk Information System (EPA IRIS) model.

EPA IRIS quantitative risk assessment

The EPA IRIS quantitative risk assessment framework was used to estimate both non-cancer and cancer risks associated with formaldehyde exposure [14]. Toxicological dose–response values were obtained from EPA IRIS, including the reference concentration (RfC) for non-cancer effects and the inhalation unit risk (IUR) for cancer risk. The RfC was 0.007 mg/m^3, and the IUR was 1.1×10^{-5} per μg/m^3, equivalent to 1.1×10^{-2} per mg/m^3.

Individual formaldehyde exposure concentrations were obtained from full-shift personal air sampling. Exposure parameters, including exposure duration (ED) in years, exposure frequency (EF) in days per year, and exposure time (ET) in hours per day, were derived from worker questionnaires. The exposure concentration (EC) was calculated using the standard EPA averaging-time equation: $EC=(CA\times ET\times EF\times ED)/AT$, where CA is the formaldehyde concentration in mg/m^3, and AT is the averaging time. For non-cancer risk, AT was calculated as $ED\times365\times24$ hours, whereas for cancer risk, AT was calculated as $70\times365\times24$ hours, or 613,200 hours.

Non-cancer risk was expressed as the HQ and calculated as HQ=EC/RfC. HQ values were interpreted as acceptable when <1.0, low to moderate when 1.0–3.0, high when 3.1–10.0, and very high when >10.0. Cancer risk was estimated as the incremental lifetime cancer risk (ILCR) using the equation ILCR=EC×IUR. ILCR values were categorized as acceptable when $<1\times10^{-6}$, moderate when 1×10^{-6}–1×10^{-4}, high when 1×10^{-4}–1×10^{-3}, and very high when $>1\times10^{-3}$. These values represent the estimated additional lifetime cancer risk among exposed workers.

Statistical analysis

Descriptive statistics (frequency, percentage, mean, SD, median, minimum, and maximum) were computed. Differences in formaldehyde concentrations, HQs, and cancer risks (CR) among departments were evaluated. Risk characterization was compared with threshold values of HQ > 1 (non-cancer) and CR>1×10^{-6} (cancer).

Agreement between the TIS 2012 semi-quantitative risk levels and the EPA IRIS quantitative HQ classifications was assessed using Cohen's kappa coefficient (κ). Kappa values and their 95% confidence intervals were interpreted using established criteria (κ<0.20=slight, 0.21–0.40=fair, 0.41–0.60=moderate, 0.61–0.80=substantial, and >0.80=almost perfect agreement). Statistical significance was set at $p<0.05$. Data were analyzed using SPSS version 21.0 (IBM Corp., Armonk, NY).

Results

Demographic and health characteristics

A total of 439 furniture workers participated in the study. The majority were female (61.3%), with a mean age of 39.8±9.0 years (range: 18–59). Prevalence of current smoking, allergic diseases, family history of allergy, and metal allergy was 19.4%, 5.7%, 8.0%, and 18.5%, respectively (**Table 1**). Workers had an average employment duration of 10.7 years (range: 0.16–39), typically working 8 hours per day and 5.96 days per week. Participants were distributed across 10 production departments with varying exposure profiles.

Table 1. Demographic and health characteristics of the participants (n=439)

Characteristics	Total (n=439)	Office staff (n=116)	Production department (n=323)
Age (year)	39.8±9.0	39.34 (8.08)	39.86 (9.83)
Sex			
Male	170 (38.7)	62 (53.4)	108 (33.4)
Female	269 (61.3)	54 (46.6)	215 (66.6)
Current smoking			
Yes	85 (19.4)	26 (22.4)	59 (18.3)
No	354 (80.6)	90 (77.6)	264 (81.7)
Allergic diseases (patch test positive)			
Yes	25 (5.7)	7 (6.0)	18 (5.6)
No	414 (94.3)	109 (94.0)	305 (94.4)
Family history of allergy			
Yes	35 (8.0)	10 (8.6)	25 (7.7)
No	392 (89.3)	105 (90.5)	287 (88.9)
Don't know	12 (2.7)	1 (0.9)	11 (3.4)
Metal allergy			
Yes	81 (18.5)	23 (19.8)	58 (18.0)
No	348 (79.3)	92 (79.3)	256 (79.3)
Don't know	10 (2.3)	1 (0.9)	9 (2.8)

Formaldehyde exposure assessment

On the basis of 100 personal air samples, the overall mean formaldehyde concentration was 5.47 mg/m³ (SD=4.79). Departmental mean concentrations ranged from 0.70 mg/m³ (Drilling) to 11.55 mg/m³ (Clearing). Above-OEL exposure was observed in nearly all departments (**Table 1**). Among production departments, the highest mean formaldehyde concentration was observed in the Clearing department (11.55 mg/m³), followed by Laminating (5.58 mg/m³), Line (5.48 mg/m³), Fitting (2.90 mg/m³), and Packing (2.32 mg/m³). These measured concentrations served as the primary exposure inputs for both the TIS 2012 semi-quantitative model and the EPA IRIS quantitative risk assessment framework (**Table 2**).

Table 2. Personal air sampling concentrations of formaldehyde among workers by department (n=100)

Department	Frequency	Concentration of formaldehyde (mg/m^3) Mean (SD)	95% confidence interval
Office	12	1.87 (1.81)	(0.72–3.03)
Production department			
Combination	10	1.11 (2.27)	(-0.52–2.73)
Edging	10	0.83 (1.76)	(-0.43–2.09)
Fitting	11	2.90 (2.46)	(1.24–4.56)
Clearing	9	11.55 (8.92)	(4.69–18.41)
Drilling	8	0.70 (0.79)	(0.03–1.37)
Laminating	10	5.58 (3.79)	(2.87–8.29)
Wrapping	10	1.73 (2.16)	(0.19–3.28)
Packing	10	2.32 (2.79)	(0.32–4.31)
Line	10	5.48 (4.79)	(2.04–8.91)
Total	100	5.47 (4.79)	(2.04–8.91)

Risk assessment results using the TIS 2012 method

Exposure assessment

On the basis of departmental CR and EF values, ER ranged from level 4 to level 5 (**Table 3**). Eight departments, Clearing, Laminating, Line, Fitting, Packing, Wrapping, Combination, and Office, were assigned ER=5, indicating very high exposure intensity, as their formaldehyde concentrations exceeded the OEL of 0.92 mg/m^3 (range: 1.11–11.55 mg/m^3, equivalent to 120–1,255% of OEL) and all operated five days per week throughout the year (EF=5) (**Table 3**). The exceptionally high concentration in the Clearing department (11.55 mg/m^3; 1,255% of OEL) reflects its role in handling accumulated dust and resin residues from multiple upstream processes. Only Edging and Drilling were classified as ER=4, reflecting a comparatively high but lower exposure intensity, with concentrations of 0.83 and 0.70 mg/m^3, respectively (**Table 3**). These ER patterns correspond to the measured concentration distributions presented in **Table 3**.

Risk characterization

Risk scores were calculated on the basis of the formula ER×HER. Eight departments, Office, Combination, Fitting, Clearing, Laminating, Wrapping, Packing, and Line, achieved a risk score of 25, corresponding to very high risk, driven primarily by formaldehyde concentrations ranging from 1.11 to 11.55 mg/m^3 (120–1,255% of OEL) combined with maximum exposure frequency and severity ratings (EF=5, HER=5) (**Table 3**). By contrast, Edging and Drilling had a risk score of 20, classified as high risk, with concentrations of 0.83 and 0.70 mg/m^3, representing 90% and 72% of the OEL, respectively. Overall, all departments demonstrated high to very high-risk levels, indicating severe workplace exposure conditions that require immediate control measures (**Table 3**).

Risk assessment results from the IRIS method

Exposure assessment

Individual formaldehyde exposure concentrations were obtained from full-shift personal air sampling across all departments. Exposure parameters (ED, EF, and ET) were derived from structured questionnaires administered to workers. The arithmetic mean exposure duration was 10.7 years (range: 0.16–39 years). Workers averaged 5.96 working days per week and 8 hours per day.

Table 3. TIS 2012 risk characterization by department (n=439 workers, n=100 personal air samples)

Department	n	Conc. (mg/m^3)	% of OEL*	CR	EF	ER	HER	Risk score	Risk level	
Office	12	1.75	190	5	5	5	5	25	5	Very high
Combination	10	1.11	120	5	5	5	5	25	5	Very high
Edging	10	0.83	90	4	5	4	5	20	4	High
Fitting	11	2.46	267	5	5	5	5	25	5	Very high
Clearing	9	11.55	1,255	5	5	5	5	25	5	Very high
Drilling	8	0.70	76	4	5	4	5	20	4	High
Laminating	10	5.58	604	5	5	5	5	25	5	Very high
Wrapping	10	1.73	188	5	5	5	5	25	5	Very high
Packing	10	1.89	205	5	5	5	5	25	5	Very high
Line	10	4.49	488	5	5	5	5	25	5	Very high
Total	100									

CR: concentration rating; EF: exposure frequency; ER: exposure rating; HER: health effect rating; OEL: occupational exposure limit

*Ministry of Labor OEL, 0.75 ppm; (0.92 mg/m^3)

Risk characterization - non-cancer risk

All departments exceeded the acceptable HQ threshold (HQ<1.0), with values ranging from 6.59 (Drilling) to 87.99 (Clearing) (**Table 4**). Five of ten departments, Fitting, Clearing, Laminating, Packing, and Line, were classified as very high risk (HQ>10.0). The Office, Combination, Wrapping, and Drilling departments, although at lower concentrations, still posed a high risk (HQ 3.1–10.0), underscoring the need for intervention across all exposure groups (**Table 4**).

Risk characterization - cancer risk

All departments exhibited lifetime cancer risks far exceeding the acceptable threshold (1×10^{-6}), with mean values ranging from 7.72×10^{-3} (Drilling) to 1.27×10^{-1} (Clearing) (**Table 5**). All ten departments were classified as very high cancer risk ($>1\times10^{-3}$), representing an unacceptable probability of additional cancer cases among exposed workers.

Divergence and concordance assessment between frameworks

The comparison revealed substantial divergence between the two assessment frameworks (**Table 6**). The TIS 2012 method classified 59.0% of samples as very high risk, while 31.0% and 9.0% were categorized as acceptable and low risk, respectively. By contrast, the EPA IRIS cancer risk assessment identified 69.0% of samples as very high risk ($>1\times10^{-3}$), and the EPA non-cancer evaluation showed 40.0% of samples with very high HQ values (HQ>10). Despite differences in exposure assumptions and toxicological benchmarks between the two frameworks, most departments were classified as high or very high risk by both methods, as shown in **Table 6**.

The comparison of formaldehyde exposure and risk characterization across departments using the TIS 2012 and EPA IRIS approaches is presented in **Table 7**. Most departments were classified as high or very high risk by both methods, although some differences in classification levels were observed.

TIS 2012 classified 8 of 10 departments (80%) as very high risk, compared with 5 of 10 departments (50%) under EPA IRIS. The five departments concordantly rated very high by both models (Fitting, Clearing, Laminating, Packing, and Line) accounted for the majority of overlap, while Office, Combination, and Wrapping were classified as very high only under TIS 2012 Notably, lifetime cancer risk estimates exceeded acceptable thresholds across all departments under the EPA IRIS model in **Table 7**.

Summary of risk assessment agreement analysis

The two classification systems were cross-tabulated (Table 8), 73.0% of the 100 individual air samples received concordant risk designations — 31.0% classified as low by both methods, 4.0% as medium, and 38.0% as very high. The remaining 27.0% showed one-level discordance, driven predominantly by samples that TIS 2012 placed in the very high category but EPA IRIS HQ assigned to low (12.0%) or medium (9.0%); no two-level disagreements were observed. A Cohen's kappa of 0.554 (95%CI 0.422–0.686; $p<0.001$) indicated moderate agreement between the two approaches in **Table 8**.

Table 4. Departmental non-cancer risk assessment based on EPA IRIS hazard quotient (HQ), n=100 personal air samples

Depart	n	Exposure concentration, mean (SD) (mg/m^3)	Hazard quotient, mean (SD)	Hazard quotient range (min–max)	P25–P50	Risk level
Office	12	0.009 (0.0005)	7.51 (8.19)	0.00–19.97	0.16–3.78	High
Combination	10	0.006 (0.000)	8.17 (16.40)	0.00–42.19	0.00–0.00	High
Edging	10	0.004 (0.000)	1.67 (2.78)	0.00–7.23	0.00–0.00	Low to moderate
Fitting	11	0.013 (0.000)	16.46 (21.07)	0.00–60.03	0.00–0.00	Very high
Clearing	9	0.059 (0.000)	87.99 (72.60)	0.00–240.57	26.08–94.40	Very high
Drilling	8	0.004 (0.000)	6.59 (12.79)	0.00–36.00	0.00–0.33	High
Laminating	10	0.013 (0.013)	42.44 (40.83)	1.22–114.99	2.75–33.65	Very high
Wrapping	10	0.009 (0.000)	8.89 (12.40)	0.00–35.63	0.00–3.39	High
Packing	10	0.010 (0.000)	21.50 (50.61)	0.00–164.19	0.53–1.88	Very high
Line	10	0.025 (0.000)	27.47 (26.32)	0.00–81.63	4.20–22.69	Very high
Total	100	0.013 (0.013)	22.17 (39.28)	0.00–240.57	4.99–114.88	Very high

EPA IRIS: United States Environmental Protection Agency Integrated Risk Information System; RfC: reference concentration; P25–P50: 25th–50th percentile range of hazard quotient (HQ) values (unitless). Exposure concentration (EC) values represent departmental means from personal air sampling. EC was assigned equally to all workers within each department based on the Similar Exposure Group (SEG) approach; therefore, SD of EC=0 within departments. HQ was calculated using the EPA IRIS model (RfC=0.007 mg/m^3). Risk interpretation: HQ<1.0=acceptable; 1.0–3.0=low to moderate; 3.1–10.0=high; >10.0=very high (requiring immediate action).

Table 5. Lifetime cancer risk by department based on the United States Environmental Protection Agency Integrated Risk Information System (EPA IRIS) model (n=439 workers, n=100 personal air samples)

Department	Number of samples	Exposure concentration, mean (SD) mg/m^3 [a]	Incremental lifetime cancer risk (ILCR) [b]				Cancer risk level
			Mean	Range (min–max)	95% CI: lower	upper	
Office	12	0.002 (0.001)	2.06×10^{-2}	$0.00–5.69\times10^{-2}$	7.89×10^{-3}	3.33×10^{-2}	Very High
Combination	10	0.001 (0.001)	1.22×10^{-2}	$0.00–7.26\times10^{-2}$	-5.74×10^{-3}	3.00×10^{-2}	Very High
Edging	10	0.001 (0.000)	9.15×10^{-3}	$0.00–6.09\times10^{-2}$	-4.74×10^{-3}	2.30×10^{-2}	Very High
Fitting	11	0.001 (0.001)	3.19×10^{-2}	$0.00–8.07\times10^{-2}$	1.37×10^{-2}	5.01×10^{-2}	Very High
Clearing	9	0.013 (0.01)	1.27×10^{-1}	$5.86\times10^{-3}–2.82\times10^{-1}$	5.16×10^{-2}	2.02×10^{-1}	Very High
Drilling	8	0.000 (0.000)	7.72×10^{-3}	$0.00–2.30\times10^{-2}$	3.69×10^{-4}	1.51×10^{-2}	Very High
Laminating	10	0.003 (0.003)	6.14×10^{-2}	$5.22\times10^{-3}–1.62\times10^{-1}$	3.15×10^{-2}	9.13×10^{-2}	Very High
Wrapping	10	0.001 (0.001)	1.91×10^{-2}	$0.00–5.56\times10^{-2}$	2.06×10^{-3}	3.61×10^{-2}	Very High
Packing	10	0.001 (0.001)	2.55×10^{-2}	$0.00–8.87\times10^{-2}$	3.48×10^{-3}	4.75×10^{-2}	Very High
Line	10	0.0038 (0.023)	6.02×10^{-2}	$0.00–1.89\times10^{-1}$	2.25×10^{-2}	9.80×10^{-2}	Very High
Total	100	0.002 (0.0035)	3.68×10^{-2}	$0.00–2.82\times10^{-1}$	2.65×10^{-2}	4.71×10^{-2}	Very High

[a] Exposure concentration values represent departmental means from personal air sampling.
[b] ILCR was calculated using the US EPA IRIS model (IUR=1.1×10^{-2} per mg/m^3). Risk interpretation: ILCR<1×10^{-6}=acceptable; 1×10^{-6}–1×10^{-4}=moderate; 1×10^{-4}–1×10^{-3}=high; >1×10^{-3}=very high (unacceptable lifetime cancer risk).

Table 6. Comparison of risk characterization between TIS 2012 (ER×HER) and EPA IRIS (HQ and lifetime cancer risk) by personal air samples (n=100 personal air samples)

Department	n=100	TIS 2012					EPA IRIS							
		Risk level; n (%)					HQ level; n (%)				Lifetime cancer risk; n (%)			
		0	1	2	3	4	1	2	3	4	1	2	3	4
Office	12	0 (0)	3 (9.7)	0 (0)	0 (0)	9 (15.3)	5 (13.5)	1 (10.0)	1 (12.5)	5 (12)	3 (10.3)	0 (0)	0 (0)	9 (13.1)
Combination	10	0 (0)	7 (22.6)	1 (11.1)	0 (0)	2 (3.4)	7 (18.9)	0 (0)	1 (7.7)	2 (5.0)	6 (20.7)	1 (100)	0 (0)	3 (4.3)
Edging	10	0 (0)	7 (22.6)	0 (0)	0 (0)	3 (5.1)	7 (18.9)	0 (0)	3 (23.1)	0 (0)	7 (24.1)	0 (0)	0 (0)	3 (4.3)
Fitting	11	0 (0)	3 (9.7)	0 (0)	0 (0)	8 (13.6)	4 (10.8)	1 (10.0)	2 (15.4)	4 (10)	2 (6.9)	0 (0)	1 (100)	8 (11.6)
Clearing	9	0 (0)	0 (0)	2 (22.2)	0 (0)	7 (11.9)	0 (0)	0 (0)	2 (15.4)	7 (17.5)	0 (0)	0 (0)	0 (0)	9 (13.0)
Drilling	8	0 (0)	3 (9.7)	2 (22.2)	0 (0)	3 (5.1)	5 (13.5)	1(10)	0 (0)	2 (5.0)	3 (10.3)	0 (0)	0 (0)	5 (7.2)
Laminating	10	0 (0)	0 (0)	1 (11.1)	0 (0)	9 (15.3)	0 (0)	3 (30.0)	0 (0)	7 (17.5)	0 (0)	0 (0)	0 (0)	10 (14.5)
Wrapping	10	0 (0)	5 (16.1)	0 (0)	0 (0)	5 (8.5)	5 (13.5)	0 (0)	2 (15.4)	3 (7.5)	5 (17.2)	0 (0)	0 (0)	5 (7.2)
Packing	10	0 (0)	2 (6.5)	3 (33.3)	0 (0)	5 (8.5)	3 (8.1)	3 (30.0)	0 (4)	4 (10)	2 (6.9)	0 (0)	0 (0)	8 (11.6)
Line	10	0 (0)	1 (3.2)	0 (0)	1 (100)	8 (13.6)	1 (2.7)	1 (10)	2 (15.4)	6 (15.0)	1 (3.4)	0 (0)	0 (0)	9 (13.0)
Total	100	0 (0)	31 (100)	9 (100)	1 (100)	59 (100)	37 (100)	10 (100)	13 (100)	40 (100)	29 (100)	1 (100)	1 (100)	69 (100)

EPA IRIS: United States Environmental Protection Agency Integrated Risk Information System; HER: health effect rating; HQ: hazard quotient; TIS: Thai Industrial Standard.
TIS 2012: 1–3=acceptable (0); 4–9=low (1); 10–16=medium (2); 17–20=high (3); 21–25=very high (4)
IRIS EPA HQ level: <1 acceptable (1); 1–3 low-mod (2); 3.1–10 high (3); >10 very high (4)
Lifetime cancer risk: $<1\times10^{-6}$ low (1); 1×10^{-6}–1×10^{-4} moderate (2); 1×10^{-4}–1×10^{-3} high (3); $>1\times10^{-3}$ very high (4)

Table 7. Summary of formaldehyde exposure and risk characterization across departments using TIS 2012 and EPA IRIS

Department	TIS 2012				EPA IRIS			
	n (workers)	Mean concentration (mg/m³)	%OEL	Risk level	Mean HQ	HQ level	Mean cancer risk	Cancer level
Office	116	1.75	190	Very High	7.51	High	2.06×10^{-2}	Very High
Combination	39	1.11	120	Very High	8.17	High	1.22×10^{-2}	Very High
Edging	51	0.83	90	High	1.67	Low to Moderate	9.15×10^{-3}	Very High
Fitting	34	2.46	267	Very High	16.46	Very High	3.19×10^{-2}	Very High
Clearing	22	11.55	1255	Very High	87.99	Very High	1.27×10^{-1}	Very High
Drilling	50	0.66	72	High	6.59	High	7.72×10^{-3}	Very High
Laminating	27	5.58	604	Very High	42.44	Very High	6.14×10^{-2}	Very High
Wrapping	28	1.73	188	Very High	8.89	High	1.91×10^{-2}	Very High
Packing	55	1.89	205	Very High	21.50	Very High	2.55×10^{-2}	Very High
Line	17	4.49	488	Very High	27.47	Very High	6.02×10^{-2}	Very High

EPA IRIS: United States Environmental Protection Agency Integrated Risk Information System; HQ: hazard quotient; OEL: occupational exposure limit; TIS: Thai Industrial Standard.

Table 8. Agreement between TIS 2012 and EPA IRIS HQ classifications based on individual air samples (n=100)

TIS 2012	EPA IRIS hazard quotient; n (%)				Cohen's Kappa (κ)
	Low	Medium	Very high	Total	
Low	31 (31.0)	0 (0.0)	0 (0.0)	31 (31.0)	κ=0.554
Medium	4 (4.0)	4 (4.0)	2 (2.0)	10 (10.0)	95%CI: 0.422–0.686
Very high	12 (12.0)	9 (9.0)	38 (38.0)	59 (59.0)	p<0.001
Total	47 (47.0)	13 (13.0)	40 (40.0)	100 (100.0)	Moderate agreement

EPA IRIS: United States Environmental Protection Agency Integrated Risk Information System; TIS: Thai Industrial Standard.

Discussion

The present study revealed a mean formaldehyde concentration of 5.47 mg/m³, with the Clearing department recording the highest level at 11.55 mg/m³ (1,255 % of the OEL) [11]. These levels confirm that MDF furniture manufacturing represents a high-risk environment, consistent with previous studies reporting exposure concentrations exceeding 2–5 mg/m³ in similar industrial settings [19,20].

Comparable studies in Asian MDF factories have reported exposure ranges of 2.8–4.5 mg/m³ [21], which align closely with the overall mean observed in this study, whereas substantially lower concentrations have been documented in European facilities (0.3–1.2 mg/m³), where stricter occupational exposure limits and advanced engineering controls are systematically implemented [22]. Based on this comparison, differences in process temperature, resin usage intensity, and ventilation efficiency may likely drive inter-departmental variability and increased exposure levels in MDF manufacturing.

In the present study, the EPA IRIS assessment revealed consistently elevated non-cancer risks across all departments, with HQs ranging from 6.59 to 87.99, far exceeding the acceptable threshold (HQ=1.0) and reference concentration (0.007 mg/m³) [14]. The Clearing department showed the highest risk, while Drilling, though lowest, remained above safe levels, suggesting that all workers experienced unacceptable chronic exposure. The wide variability in HQ values across departments (6.59–87.99) likely reflects differences in formaldehyde concentrations, working hours, and proximity to emission sources, particularly from hot-pressing operations in upstream processes. These findings are consistent with previous studies reporting elevated HQs and associated respiratory and systemic effects among MDF and furniture workers [23]. Further evidence from other studies demonstrates that even sub-OEL exposures can induce airway inflammation and oxidative stress [22,24], which supports the interpretation that OEL compliance alone is insufficient to protect against chronic risk. Based on these findings and supporting literature, immediate interventions are therefore required, including strengthened engineering controls, improved ventilation, and comprehensive respiratory protection programs. Given formaldehyde's classification as an IARC Group 1 carcinogen [8], the sustained exposure levels observed in this study may further increase long-term health risks.

These findings are consistent with previous studies reporting elevated HQs and associated respiratory and systemic effects among MDF and furniture workers [23]. Evidence further demonstrates that even sub-OEL exposures can induce airway inflammation and oxidative stress [22,24], supporting the interpretation that OEL compliance alone is insufficient to protect against chronic risk. However, it should be noted that the EPA IRIS model applies standardized assumptions, including a 70-year lifetime exposure duration and population-averaged toxicokinetic parameters, which may not fully reflect actual working conditions or individual susceptibility among Thai MDF workers and may therefore overestimate or underestimate the true risk. Based on these findings and supporting literature, urgent interventions are therefore required, including strengthened engineering controls, improved ventilation, and comprehensive respiratory protection programs to mitigate sustained formaldehyde exposure and its associated chronic health effects.

The EPA IRIS quantitative model estimates lifetime cancer risk using an IUR of 1.1×10^{-5} per μg/m³. The mean lifetime cancer risk in this study (3.68×10^{-2}) substantially exceeded the acceptable threshold (1×10^{-6}), with all departments classified as very high risk ($>1\times10^{-3}$). The

Clearing department exhibited the highest risk (1.27×10^{-1}), consistent with increased exposure during resin curing and finishing. These values exceed those reported in comparable occupational settings (7.55×10^{-6}–2.58×10^{-4}) [23]. Several factors may explain this difference. First, the formaldehyde concentrations observed in this study (mean 5.47 mg/m^3; maximum 11.55 mg/m^3) were substantially higher than those reported in previous studies, likely reflecting less stringent emission controls and higher resin usage intensity in Thai MDF manufacturing. Second, the exposure parameters used in this study, including actual employment duration (ED), working days per year (EF), and daily working hours (ET) derived from worker questionnaires, may differ from the standardized assumptions used in other studies, resulting in higher estimated lifetime exposure. Third, the EPA IRIS model used a linear no-threshold assumption for carcinogenic risk, which may yield higher estimates than those from other calculation methods used in other countries. These factors indicate that the exposure controls in this facility were insufficient. Formaldehyde's classification as an IARC Group 1 carcinogen increases this concern, as it has established links to nasopharyngeal cancer and leukemia [8,22,26]. The U.S. EPA has similarly concluded that formaldehyde poses unacceptable health risks in poorly controlled occupational settings [14]. These findings highlight the urgent need for intervention, including enhanced engineering controls, low-emission adhesives, improved local exhaust ventilation, and adherence to WHO indoor air guidelines (<0.1 mg/m^3) [27], reinforcing exposure reduction in MDF manufacturing as a critical occupational health priority.

High concordance (80%) between the TIS 2012 [13] and EPA IRIS models [14] indicates that both approaches reliably identify clearly high-risk exposures. However, the discrepancy observed in the Drilling department demonstrates that OEL-based assessments may underestimate chronic toxicological risks, particularly for carcinogens, even when exposures remain below regulatory limits. Formaldehyde’s mode of action, via DNA-protein crosslinking and its established carcinogenicity, supports this concern, as moderate exposures can still produce unacceptable lifetime cancer risks [14,28].

The Drilling department illustrates this limitation. Although classified as high risk under TIS 2012, the quantitative assessment revealed an HQ of 6.59 and a lifetime cancer risk of 7.72×10^{-3}, far exceeding acceptable thresholds. Similar underestimation by semi-quantitative tools has been reported in other industries, particularly for carcinogens [29]. These findings support adopting hybrid risk assessment protocols in Thailand, maintaining TIS 2012 for initial screening while mandating quantitative evaluation for Group 1 carcinogens or exposures exceeding 50% of the OEL.

The moderate agreement between TIS 2012 [13] and the EPA IRIS [14] Hazard Quotient model (κ=0.554, 73.0% concordance) indicates that both methods generally classify formaldehyde risk similarly. However, the 27.0% one-level discrepancies suggest that the semi-quantitative nature of TIS 2012, which is widely applied in Thailand, may differ in sensitivity from quantitative toxicological models in specific exposure scenarios, particularly for chronic or carcinogenic hazards. These findings align with previous observations that semi-quantitative tools are less sensitive than quantitative toxicological models in detecting elevated health risks [8,29,30]. While TIS 2012 remains practical for routine workplace assessments due to its simplicity and cost-effectiveness, it may still serve as an acceptable screening tool for initial hazard identification, provided that positive findings are followed up with quantitative dose–response assessments, such as those from the EPA IRIS database, to improve the accuracy of risk characterization. This integrated approach would support more robust occupational health decision-making, particularly for Group 1 carcinogens [8], where threshold-based approaches may be inadequate.

The findings highlight important implications for long-term worker health. Although the TIS 2012 [13] semi-quantitative approach is helpful for preliminary screening, it substantially underestimates both non-cancer and cancer risks relative to the quantitative EPA IRIS [14] framework. Such underestimation may delay necessary interventions and prolong exposure to carcinogenic levels of formaldehyde. Integrating semi-quantitative and quantitative assessment models provides a more accurate risk profile; enables the prioritization of high-risk departments; and supports the implementation of evidence-based engineering controls, ventilation improvements, and respiratory protection programs to safeguard worker health.

Very high-risk departments, particularly, should be prioritized for immediate intervention. Mandatory respiratory protection programs using formaldehyde-rated cartridges or filters should be established and supported by quantitative fit testing, routine exposure monitoring, and medical surveillance to detect early respiratory or mucosal effects. Engineering controls, including enhanced local exhaust ventilation and process isolation, should be implemented or upgraded. Annual competency-based training aligned with Thai OSH regulations is recommended to reinforce hazard awareness and proper PPE use [11,12].

This study has several limitations. First, personal air sampling was conducted during routine operations and may not fully capture peak or task-specific exposure variability, potentially underestimating short-term exposure spikes. Second, the study did not assess the effectiveness of existing engineering controls, ventilation performance, or PPE compliance, which limits the ability to link exposure levels to specific preventive measures. Third, the cross-sectional design precludes drawing conclusions about long-term health outcomes or exposure–response relationships. Fourth, the cross-sectional design cannot establish causal relationships; observed associations should be interpreted as correlational rather than causal. Fifth, simultaneous measurement of exposure and outcomes makes it unclear whether exposure preceded or followed the observed health effects, and future longitudinal studies are warranted to clarify these relationships. Despite these constraints, the findings reinforce the need to apply the hierarchy of controls to mitigate formaldehyde exposure in MDF manufacturing environments.

Building on the demonstrated underestimation by TIS 2012, future research should develop user-friendly risk assessment applications that employ a two-tier approach: an initial semi-quantitative screening (TIS, 2012) to identify high-risk scenarios, followed by automated quantitative assessment (EPA IRIS) to calculate HQ and cancer risk, with actionable, risk-level-specific control recommendations made in real time.

Conclusions

Quantitative analysis revealed that OEL-based, semi-quantitative assessments such as TIS 2012 substantially underestimate the risks associated with carcinogenic exposures, particularly for formaldehyde. Incorporating both acute and chronic endpoints through a quantitative framework, such as EPA IRIS, provides a more comprehensive and health-protective evaluation of long-term exposures. The Clearing department demonstrated the highest non-cancer and cancer risks, indicating an immediate need for engineering controls, improved ventilation, and periodic medical surveillance. More broadly, integrating quantitative risk assessment into routine occupational health practice in Thailand would enhance decision-making, strengthen preventive strategies, and elevate worker protection beyond compliance-driven standards.

Ethics approval

The study was approved by the Burapha University Human Research Ethics Committee (No. 381/2556), and all participants provided written informed consent.

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Competing interests

The authors declare that there is no conflict of interest.

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Underlying data

Derived data supporting the findings of this study are available from the corresponding author on request.

Declaration of artificial intelligence use

We hereby confirm that no artificial intelligence (AI) tools or methodologies were utilized at any stage of this study, including during data collection, analysis, visualization, or manuscript preparation. All work presented in this study was conducted manually by the authors without the assistance of AI-based tools or systems.

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