

Occurrence of formaldehyde exposures in work activities and its diffusion in the Italian industrial context following the notification requirements

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Abstract

Purpose. The aim of this study is to describe data on occupational exposure to formaldehyde in the context of Italian economic activities.

Methods. Measurement data of airborne concentrations (n=26,216) of formaldehyde in the period 1996-2024 were selected from the national register of occupational exposure to carcinogens (Sistema Informativo Registri di Esposizione Professionale, SIREP). Descriptive statistics were calculated for main exposure-related variables. The number of potentially exposed workers was estimated for the best-characterized sectors.

Results. The overall geometric mean was 0.028 mg/m³. Most of the exposure was found in the wood (n=4,912), chemical (n=4,090), and plastic industries (n=3,925). A different distribution of exposure was found according to gender, as women exposures were more common in the healthcare sector. The estimated number of potentially exposed workers in the selected sectors was approximately 100,000.

Conclusions. The implementation of the new European Union (EU) regulation has enhanced the surveillance system, resulting in noteworthy improvements in the monitoring of occupational exposure to formaldehyde.

Key words

- formaldehyde
- exposure assessment
- occupational health
- surveillance system

INTRODUCTION

Formaldehyde, a well-known chemical, is the simplest of the aldehydes with a structural formula consisting of a carbonyl group (C=O) to which two hydrogen atoms are bonded, making the molecule highly reactive at ambient temperature. It occurs naturally as a colourless gas [1]. This substance is listed by the World Health Organization (WHO) as a pollutant of public health concern, known for its adverse effects [2]. In the environment formaldehyde is ubiquitous, both as a primary and secondary pollutant, released directly from combustion processes, including several natural sources, industrial emissions, and urban traffic, or formed in the atmosphere by photochemical reactions of other pollutants, such as volatile organic compounds [2]. It is a known respiratory and skin irritant, and can cause long-term damage, including eye irritation, allergies, and even genetic damage and cancer [1]. Exposure occurs primarily through inhalation into the respiratory tract or skin absorption. It is rapidly absorbed after inhalation and oral exposure, but it is poorly absorbed through the skin [1]. The International Agency for Research on

Cancer (IARC) has classified it as a Group 1 carcinogen to human since 2012 [3]. The carcinogenicity of formaldehyde is mainly due to its ability to cause cross-links between DNA and proteins and cellular toxicity at the point of contact [3]. There is an ongoing debate about whether its carcinogenic mechanism is threshold (non-genotoxic) or non-threshold (genotoxic), but some leading scientific institutions currently consider it a non-threshold carcinogen, meaning that even low-level exposure may pose a risk, especially for nasopharyngeal cancer and some types of leukaemia [1-3]. Formaldehyde is widely used in different industrial and professional sectors due to its properties as a preservative, disinfectant and fixative agent. It is primarily used in the manufacture of resins, preservatives, lawn fertilizers, fixatives, cosmetics, and disinfectants, and workers involved in its production or use may be exposed to dangerous levels during their work activities [1, 2]. In 2016, with the entry into force of European Union (EU) Regulation n. 605/2014, the obligation to report occupational exposure to carcinogens to the national register (Sistema Informativo Registri di Esposizione

Professionale, SIREP) established by National Institute for Insurance against Accidents at Work (Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro, INAIL) was extended to include formaldehyde, which is now among the substances classified in Group 1B of the EU classification pursuant to the Regulation n. 1272/2008. To prevent and control exposure through inhalation, the EU regulation requires, from 2020, an 8-hour occupational exposure limit value (OELV) of 0.37 mg/m³ of formaldehyde in the workplace air. The OELV for formaldehyde has traditionally been based on both animal and human studies demonstrating its irritant properties and carcinogenic potential, highlighting significant risks at concentrations above certain levels. Given the evolving scientific evidence and new insights into genotoxicity and susceptible populations, there are compelling reasons to continue updating this limit value. However, there is no scientific evidence for the feasibility of assessing formaldehyde exposure through biological monitoring, and no biological indicators are available for this purpose.

The aim of this study is to describe the level of exposure to formaldehyde in different sectors of activity and occupational groups in Italy following the entry into force of the reporting obligation. An estimation of the number of workers potentially exposed to formaldehyde was also performed.

METHODS

Data collection

The measurement data on formaldehyde exposure were collected by SIREP and refer to the exposure period 1996-2024. SIREP is a relational database whose design and contents have been extensively described elsewhere [4]. In summary, according to Italian regulation on health surveillance in the workplace (Legislative Decree n. 81/2008), employers are required to record data on occupational exposure to carcinogens and notify them to the SIREP system every three years. Exposure levels must not exceed the OELVs established in Annex XLIII of Decree n. 81/2008 and exposure measurements must be aimed at managing exposure below this binding value (residual exposure). Exceeding these limits requires the employer to intervene immediately to reduce exposure and adopt appropriate prevention and protection measures. The reporting is mandatory for workers exposed to carcinogenic agents classified as Group 1A and 1B by the European Union (1A, substance known to be carcinogenic to humans; 1B, substances that should be considered carcinogenic to humans) under EU Regulation n. 1272/2008 on the classification, labelling and packaging of chemicals. Formaldehyde has been classified in Group 1B since 2016; prior to this year, data was notified to the system only on a voluntary basis. The management and transmission of data have to be completed exclusively electronically via a web application. The main information provided by employers includes the economic activity and size of the firm, the demographic and occupational data of the workers, and the levels of exposure in terms of intensity, frequency, and time duration. One or more exposure measurements are recorded for each

worker and work period. Employers are responsible for exposure measurement procedures and air sampling methods, to be carried out in accordance with European standards which provide technical guidance on the implementation of air monitoring strategies [5].

Data selection and classification

A total of 26,216 measurements that refer to 19,242 exposure situations to formaldehyde were selected; 4,446 exposures of which were measured repeatedly over time. The term "exposure" refers to a specific job task of a worker that involves exposure to formaldehyde. Measurements (n=1,826) provided in parts per million (ppm) were converted to mg/m³ using the standard conversion factor derived at 25 °C and 1 atmosphere of pressure (1 ppm=1.23 mg/m³). The sample typology (*personal* or *environmental*) and the analytical method performed to collect the measurements were not always available (available percentage: 78% and 89% of cases respectively), while the sampling period was a typical 8-h working day (time-weighted average, TWA-8). The exposure-related variables selected for the descriptive analysis were the activity sector, the occupational group, the size and geographical location of the firms. The level of exposure was grouped into six value classes, according to the quantile distribution, to provide better readability of the data (<0.01, 0.01-0.025, 0.025-0.05, 0.05-0.1, 0.1-0.25, >0.25, unit in mg/m³). The size of the firms was expressed in terms of workforce and divided into five classes based on the number of workers: <10, 10-20, 20-50, 50-100, >100. International standard classifications were used to code economic sectors (Nomenclature statistique des Activités économiques dans la Communauté Européenne, NACE, revision 2) and occupational groups (International standard classification of occupations, ISCO-08). Descriptive statistical analyses were carried out to estimate the geometric mean (GM) of exposure levels, the geometric standard deviation (GSD) and the 25th-75th interquartile range (IQR). A temporal trend analysis of the mean level (GM) of exposure was performed. A sample size of 50 measurements was selected as the minimum number required to perform reliable descriptive statistics. Statistical analysis was performed using R software v. 4.1.3 (R Foundation for Statistical Computing, Vienna, Austria).

Estimating potential exposed workers

The SIREP system does not include all firms where workers may be exposed to formaldehyde, as its coverage depends largely on each firm's risk assessment procedures and other factors that may affect the representativeness of the data. Nevertheless, firms that notify the register to SIREP are also required to declare the total number of employees (both exposed and not exposed). This allowed to determine the percentage of exposed workers within each firm. As a result, it was possible to estimate the number of workers potentially exposed to formaldehyde in each economic sector, including those who were not recorded in SIREP but were likely at risk based on the nature of their firm's economic activities. For this purpose, only the best-characterized sectors

in the database were included to ensure greater reliability of the estimates, given that representativeness across sectors in SIREP was not uniform. The activity sectors best-characterized in the database were those where the percentage of reported workforce (exposed plus non-exposed) was more or equal than 1% of the total sector workforce resulting from national statistics on industry of the Italian Institute for Statistics (ISTAT) ($RW_i/W_i \geq 1\%$, where RW_i represents the reported workforce in SIREP, W_i represents the ISTAT total workforce, and i is the i -th activity sector) [6]. Moreover, only those sectors with a minimum of three firms reporting formaldehyde exposure in the SIREP database were included in the estimation. For the selected activity sectors, the number of workers potentially exposed to formaldehyde was reconstructed using the percentage of exposed workers in relation to both the workforce size of firms recorded in the SIREP database and the national statistics on workforce (i.e., $PE_i = W_i(E_i/RW_i)$, where PE_i =potentially exposed workers, W_i =ISTAT total workforce, E_i =SIREP exposed workers and RW_i =SIREP reported workforce). SIREP exposed workers (E_i) was the total number of workers having formaldehyde exposure measurements recorded for the i -th activity sector.

RESULTS

Overall, the GM of exposure to formaldehyde was 0.028 mg/m^3 , and was slightly higher in men (0.029 mg/m^3) than in women (0.024 mg/m^3). The distribution of exposure levels by activity sector (NACE codes), broken down by gender, is shown in *Table 1*. Considering men and women together, the wood, chemical and plastic industries accounted for about 50% of the total measurements. However, a different pattern for each gender is clear. The majority of exposures in men was found in the wood (20% of male exposure measurements), chemical industries (18%), and plastic (14%), while in women it was more concentrated in the healthcare sector (32% of female exposure measurements). The main analytical method used for sampling the exposure level was the one proposed by the National Institute for Occupational Safety and Health, NIOSH, (n. 2016) performed in 33% of the measurements, while the sample typology was *personal* in 49% of the cases. Among key industries (i.e., with a consistent number of exposure measurements), the sectors at highest risk were manufacture of wood and of products of wood for women ($GM=0.057 \text{ mg/m}^3$), and manufacture of rubber and plastic products ($GM=0.040 \text{ mg/m}^3$) for men. The distribution by occupational group reflects that by activity sector, showing the highest prevalence of exposures for woodworking-machine tool setters and operators in men (12% of male exposure measurements), and for medical and pathology laboratory technicians in women (13% of female exposure measurements). However, the occupational group with the highest level of formaldehyde exposure was manufacturing labourers ($GM=0.083 \text{ mg/m}^3$) in women, and pulp and papermaking plant operators in men ($GM=0.120 \text{ mg/m}^3$), even if the latter with a low number of measurements ($n=147$, 1% of male exposure measurements). Exposure levels by occupations are reported in *Table 2*, and

in *Table 3* exposure measurements are described by firm size and Italian macro area. *Figure 1* shows the temporal trend of exposure levels (GM) by year of measurement. Levels of exposure to formaldehyde are significantly decreasing over time, showing a consistent increase in notifications since 2016, the year the obligation came into force. Over the past few years (2019-2024) the number of formaldehyde measurements reported to SIREP has become rather constant, averaging around 2,500 per year. Almost 21% of measurements exceeded the value of 0.1 mg/m^3 , but this percentage varied widely among activity sectors. The distribution of exposure measurements by value classes, for the most common activity sectors, is described in *Figure 2*. Workers in the wood industry had a prevalence (in percentage terms) of elevated exposure levels ($>0.25 \text{ mg/m}^3$) approximately twice as high as those in the furniture industry, while the lowest value was reported in the metalworking industry (3%). The highest percentage of elevated exposure level ($>0.25 \text{ mg/m}^3$) was found in the healthcare sector representing over 17% of the class total. About one-third of the exposure measurements in the rubber and plastic industry were $>0.1 \text{ mg/m}^3$, while in the wood industry almost half of the measurements were $>0.05 \text{ mg/m}^3$. Overall, 2.3% was found to be above the official OELV established by legislation over time. Regarding firm size, the highest GM (0.032 mg/m^3) was found in the largest firms (i.e., with more than 100 workers), which also represent the highest number of measurements recorded ($n=12,821$, see *Table 3*). Most of the notifications on exposure levels came from firms located in the North-West and North-East regions of Italy (43% each), but the highest average levels were reported by firms located in the North-West area ($GM=0.041 \text{ mg/m}^3$, see *Table 3*). As regards the estimate of potentially exposed workers based on ISTAT census data, approximately one hundred thousand workers in the selected activity sectors (see methods) were found to be potentially at risk of exposure to formaldehyde, most of whom were employed in the furniture manufacturing sector (NACE rev. 2 code: 31, 33,227 exposed workers, 33% of total workers potentially exposed). The sector of health activities, however, was found to have the highest percentage of female workers potentially exposed to formaldehyde (63%). Detailed data for the selected activity sectors are shown in *Table 4*.

DISCUSSION

This study presents data on occupational exposure to formaldehyde recorded in the Italian national register (SIREP) from 1996 to 2024. Formaldehyde exposure was found to be widespread across various economic sectors, including the wood, plastic, and chemical industries. However, its presence was also remarkable in the healthcare sector, as well as in metallurgy and in the manufacturing of metal products. A similar study has already been carried out in the past on the same database, but before the obligation to report occupational exposures to the national register came into force [7]. The differences between this study and the previous one, conducted when reporting of occupational exposure to formaldehyde was voluntary, are clear. Only

Table 1
Distribution of mean levels of formaldehyde exposure, overall, by gender and activity sector (SIREP, 1996-2024)

Activity sector (NACE rev. 2 code)	N	GM	GSD	IQR
<i>Overall</i>	26,216	0.028	7.05	0.013-0.091
<i>Women</i>	4,169	0.024	12.42	0.011-0.100
Human health activities (86)	1,344	0.024	14.32	0.010-0.100
Manufacture of rubber and plastic products (22)	742	0.044	3.27	0.020-0.100
Manufacture of wood and of products of wood and cork, except furniture (16)	478	0.057	6.37	0.014-0.187
Manufacture of furniture (31)	288	0.012	6.90	0.005-0.038
Manufacture of chemicals and chemical products (20)	218	0.026	7.76	0.008-0.070
Scientific research and development (72)	179	0.032	3.67	0.010-0.120
Other manufacturing (32)	170	0.022	1.79	0.014-0.027
Manufacture of fabricated metal products, except machinery and equipment (25)	109	0.023	13.54	0.012-0.100
<i>Men</i>	22,047	0.029	6.20	0.013-0.090
Manufacture of wood and of products of wood and cork, except furniture (16)	4,434	0.035	5.65	0.018-0.089
Manufacture of chemicals and chemical products (20)	3,872	0.031	5.09	0.015-0.080
Manufacture of furniture (31)	3,296	0.015	7.74	0.010-0.040
Manufacture of rubber and plastic products (22)	3,183	0.039	5.41	0.015-0.111
Manufacture of fabricated metal products, except machinery and equipment (25)	1,019	0.021	5.90	0.008-0.050
Manufacture of basic metals (24)	870	0.042	4.43	0.022-0.114
Retail trade, except motor vehicles, motorcycles (47)	745	0.050	4.43	0.020-0.370
Human health activities (86)	549	0.031	10.57	0.010-0.105
Manufacture of paper and paper products (17)	481	0.050	6.00	0.010-0.200
Manufacture of textiles (13)	447	0.025	4.20	0.015-0.050
Manufacture of machinery and equipment nec (28)	382	0.029	4.49	0.010-0.120
Manufacture of other non-metallic mineral products (23)	236	0.049	4.85	0.020-0.086
Land transport and transport via pipelines (49)	229	0.062	4.26	0.034-0.034
Other manufacturing (32)	216	0.032	3.23	0.011-0.071
Manufacture of other transport equipment (30)	209	0.013	2.87	0.008-0.016
Manufacture of motor vehicles, trailers, semi-trailers (29)	206	0.026	3.45	0.010-0.094
Printing and reproduction of recorded media (18)	194	0.024	2.36	0.016-0.024
Waste collection, treatment and disposal activities; materials recovery (38)	175	0.007	16.46	0.005-0.033
Wholesale trade, except motor vehicles, motorcycles (46)	156	0.022	4.28	0.010-0.050
Scientific research and development (72)	151	0.022	3.94	0.009-0.064
Manufacture of electrical equipment (27)	135	0.036	3.60	0.011-0.111
Manufacture of basic pharmaceutical (21)	125	0.030	4.96	0.010-0.120
Warehousing and support activities for transportation (52)	104	0.033	24.79	0.001-0.220

SIREP: Sistema Informativo Registri di Esposizione Professionale; N: number of 8-h time-weighted average (TWA-8) exposure measurements (mg/m³); NACE: Nomenclature statistique des Activités économiques dans la Communauté Européenne; GM: geometric mean; GSD: geometric standard deviation; IQR: interquartile range, 25th-75th percentile; nec: not elsewhere classified.

one sector appears to be regularly reporting exposures even before 2016: the healthcare sector. The distribution of measurements by exposure levels (e.g., <0.1 mg/m³) from the previous study is quite confirmed [7], in analogy also to that performed within the CARcinogen Exposure (CAREX) Canada study [8]. Furthermore, a significant increase in notifications can be noted in 2016 (Figure 1), going from just over 150 in 2014 to more than 3,700 measurements recorded in 2016. In terms of prevalence of exposure, our results are also

in line with those of the CAREX Canada study, which identified 2% of high exposure, 28% of moderate exposure, and 70% of low exposure in 2016 [9].

The exposure levels presented here, as well as the distribution by sector of activity and occupation, are consistent with those found in other similar studies, as reported in a recent broad review study [10]. In the plastics industry, formaldehyde is used in various contexts, such as in the production of thermosetting phenolic resins and amino resins [3]. A formaldehyde-

Table 2
Distribution of mean levels of formaldehyde exposure by gender and occupational group (SIREP, 1996-2024)

Occupational group (ISCO-08 code)	N	GM	GSD	IQR
<i>Women</i>				
Medical and pathology laboratory technicians (3212)	542	0.027	16.67	0.010-0.133
Specialist medical practitioners (2212)	451	0.035	6.78	0.012-0.120
Woodworking-machine tool setters and operators (7523)	295	0.031	5.88	0.010-0.165
Plastic products machine operators (8142)	291	0.041	5.69	0.013-0.100
Life science technicians (excluding medical) (3141)	248	0.011	24.74	0.007-0.073
Manufacturing labourers nec (9329)	221	0.084	2.12	0.050-0.143
Wood processing plant operators (8172)	220	0.064	4.30	0.028-0.150
Cabinet-makers and related workers (7522)	205	0.011	15.53	0.002-0.074
Chemical and physical science technicians (3111)	171	0.016	5.49	0.007-0.065
Precision-instrument makers and repairers (7311)	163	0.020	1.48	0.014-0.027
Nursing associate professionals (3221)	127	0.019	3.35	0.007-0.046
Metal moulders and coremakers (7211)	101	0.061	2.82	0.050-0.100
<i>Men</i>				
Woodworking-machine tool setters and operators (7523)	2,952	0.017	9.49	0.010-0.049
Chemical products plant and machine operators (8131)	2,669	0.029	5.26	0.015-0.075
Plastic products machine operators (8142)	1,959	0.030	7.10	0.015-0.100
Cabinet-makers and related workers (7522)	1,905	0.017	8.20	0.007-0.057
Wood processing plant operators (8172)	1,447	0.051	3.06	0.038-0.092
Toolmakers and related workers (7222)	1,229	0.071	2.69	0.062-0.129
Metal moulders and coremakers (7211)	818	0.048	3.69	0.029-0.116
Agricultural/industrial machinery mechanic/repairer (7233)	750	0.037	3.98	0.020-0.120
Shop sales assistants (5223)	712	0.050	4.20	0.020-0.370
Assemblers nec (8219)	661	0.017	2.47	0.010-0.017
Metal finishing, plating, coating machine operators (8122)	553	0.011	5.60	0.004-0.036
Manufacturing labourers not elsewhere classified (9329)	437	0.066	3.85	0.040-0.148
Lifting truck operators (8344)	400	0.037	1.92	0.040-0.050
Painters and related workers (7131)	375	0.028	4.02	0.020-0.050
Chemical and physical science technicians (3111)	351	0.016	4.61	0.007-0.070
Bleaching/dyeing/fabric cleaning machine operators (8154)	299	0.027	2.99	0.015-0.050
Specialist medical practitioners (2212)	298	0.037	6.76	0.010-0.122
Printers (7322)	274	0.084	3.27	0.019-0.200
Heavy truck and lorry drivers (8332)	233	0.060	4.24	0.034-0.034
Electrical line installers and repairers (7413)	233	0.043	2.55	0.027-0.090
Medical and pathology laboratory technicians (3212)	193	0.032	12.25	0.010-0.150
Freight handlers (9333)	182	0.045	8.10	0.020-0.162
Metal processing plant operators (8121)	160	0.051	2.83	0.019-0.110
Pulp and papermaking plant operators (8171)	147	0.120	1.70	0.108-0.200
Stock clerks (4321)	144	0.032	5.92	0.015-0.100
Incinerator and water treatment plant operators (3132)	136	0.010	2.53	0.005-0.031
Precision-instrument makers and repairers (7311)	122	0.015	1.68	0.011-0.025
Manufacturing supervisors (3122)	115	0.037	4.02	0.015-0.089
Process control technicians nec (3139)	105	0.052	3.08	0.020-0.116
Chemists (2113)	104	0.002	129.9	0.003-0.050

SIREP: Sistema Informativo Registri di Esposizione Professionale ISCO: International standard classification of occupations; N: number of 8-h time-weighted average (TWA-8) exposure measurements (mg/m³); GM: geometric mean; GSD: geometric standard deviation; IQR: interquartile range, 25th-75th percentile; nec: not elsewhere classified.

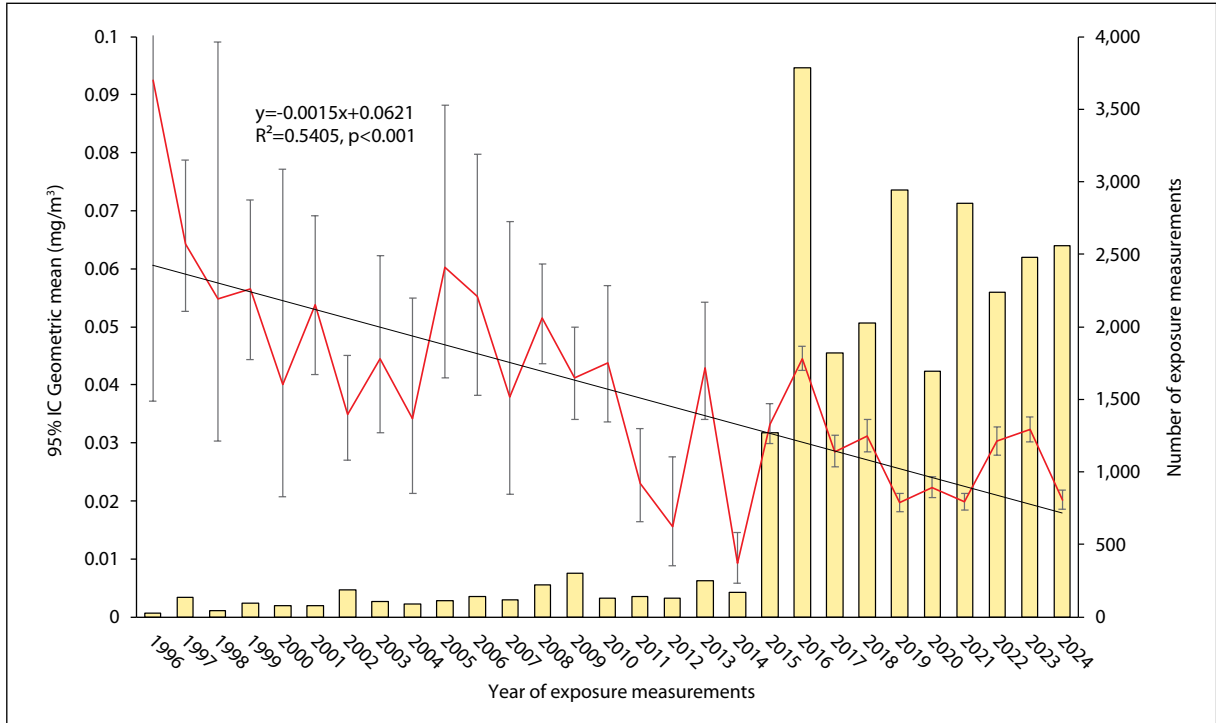


Figure 1

Temporal trend of formaldehyde exposure level and number of measurements by calendar year in Italy (Sistema Informativo Registri di Esposizione Professionale, SIREP 1996-2024); y: geometric mean; R²: coefficient of determination.

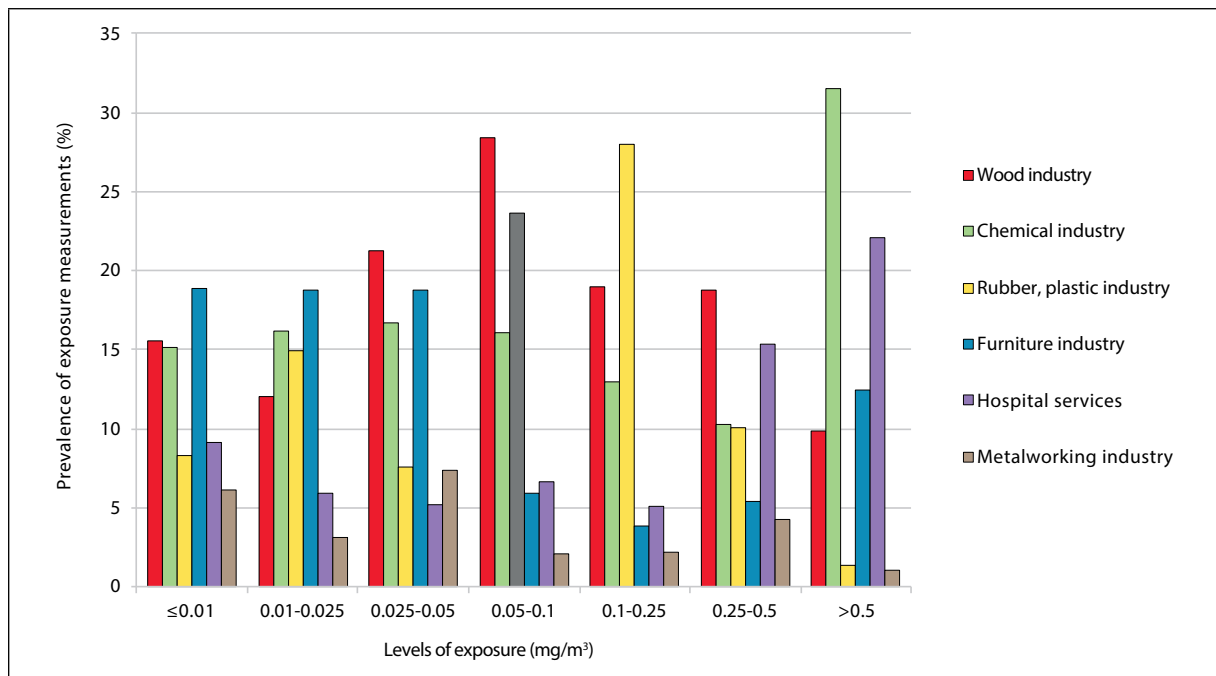


Figure 2

Distribution (%) of formaldehyde exposure measurements by value classes for the main activity sectors (Sistema Informativo Registri di Esposizione Professionale, SIREP 1996-2024).

induced toxicity study found significantly higher levels of exposure for workers in a plastic laminate industry compared to controls [11]. In the wood industry, formaldehyde finds wide application in the use of urea resins to produce particleboard, medium density fibreboard,

and plywood [3]. In a cohort analysis of Finnish men exposed to wood dust and formaldehyde, workers exposed to formaldehyde had a relative risk of 1.18 (CI 95%=1.12-1.25) for lung cancer [12]. Woodworkers were exposed to significantly higher amounts of wood

Table 3
Distribution of mean levels of formaldehyde exposure by firm size and by Italian macro area (SIREP, 1996-2024)

Firm size/Macro area	N	GM	GSD	IQR
Firm size				
<10 workers	1,492	0.029	8.32	0.010-0.095
10-20 workers	2,474	0.018	10.47	0.007-0.060
20-50 workers	4,258	0.024	7.66	0.012-0.060
50-100 workers	5,171	0.029	6.96	0.011-0.092
>100 workers	12,821	0.032	6.07	0.016-0.100
Macro area of Italy				
North-West	11,186	0.041	5.26	0.020-0.106
North-East	11,170	0.021	8.62	0.010-0.063
Centre	2,480	0.026	4.58	0.010-0.064
South and Islands	1,380	0.023	12.75	0.014-0.091

SIREP: Sistema Informativo Registri di Esposizione Professionale; N: number of 8-h time-weighted average (TWA-8) exposure measurements (mg/m³); GM: geometric mean; GSD: geometric standard deviation; IQR: interquartile range, 25th-75th percentile.

dust and formaldehyde than controls in an oxidative stress induction study [13]. In the healthcare, formalin is used for its important preservative and cell-fixing properties, finding wide application in pathological anatomy [3]. However, our results showed lower mean (GM) values in this sector than in the other most affected industrial sectors (i.e., chemical, plastic and wood industries), in line with a health risk assessment study [14], probably due to a wider use of local exhaust ventilation [15]. A recent study on historical occupational exposure to formaldehyde in China found that most measurements came from the wood industry (e.g., production of veneer sheets and wood-based panels), and several occupational groups had elevated mean concentrations, including life sciences professionals, wood processing plant operators, and rubber and plastic-products machine operators [16]. A decreasing trend in mean exposure levels over time was also noted, and all of these findings are consistent with the main results of our study. The simultaneous increase in notifications and decrease in average exposure levels to

formaldehyde observed in this study (Figure 1) could be attributed to several factors. Firstly, a reporting effect may be at play, where increased awareness and regulatory requirements encourage more frequent reporting of exposures, even as overall exposure levels decrease due to improved workplace practices. Methodological diversity in exposure measurement, including variations in sampling techniques and analytical methods over time, further complicates the interpretation of trends. Women represent a small but appreciable percentage of workers exposed to formaldehyde (about 16%), confirming the presence of a heavily gender segregation in the EU labor market across activity sectors and occupations [17]. In the healthcare sector, a prevalence of female workers was found (about 70% of total sector exposure measurements), while in other sectors a predominance of male workers was noted (a range between 80% and 95% of total sector exposure measurements). Noteworthy is the lack of data in the sector of other personal service activities (e.g., hairdressing and other beauty treatments), which is likely due to the ban on the direct use of formaldehyde in cosmetic products in the EU since 2019 [18]. Differences in distribution by geographical area of Italy may reflect the different distribution of industry types among Italian regions. The higher GM value for the North-West could be due to the high level of industrialization in that area of economic sectors at high risk for formaldehyde exposure resulting from our study, particularly in the industrial district between Milan, Turin, and Genoa [19]. The sectors identified as at high risk in this study may be the subject of information and training campaigns on prevention and protection measures aimed at raising awareness among workers and employers.

The estimated number of potentially exposed workers (about 100,000) is in line with the latest assessment under the CAREX Canada project (about 117,000 Canadians estimated to be exposed to formaldehyde at work in 2016), taking due account of the size and structure of the target population [9]. The difference between the estimate of this study and that of CAREX for Italy (about 115,000) could be due to the smaller number of sectors considered here and to the difference in the collection and estimation methods [20]. In the near future,

Table 4
Estimates of workers potentially exposed in the selected sector of economic activities (SIREP, 1996-2024)

Sector of economic activity (NACE rev. 2 code)	N. of firms ^a	% of firms ^b	N. of workers ^c	% of workers ^d	% of exposed ^e	N. of exposed ^f	% of men
Wood industry (16)	66	0.8	2,549	7.2	34.3	13,080	82.5
Chemical industry (20)	46	1.7	3,140	6.0	27.1	15,823	81.4
Rubber, plastic industry (22)	27	0.3	1,154	1.2	25.6	25,367	71.6
Metallurgical industry (24)	8	3.0	827	20.9	8.7	337	95.5
Metalworking industry (25)	34	0.8	1,108	3.1	28.1	10,161	77.0
Furniture industry (31)	85	0.6	3,507	3.1	29.8	33,227	73.5
Hospital services (86)	44	0.4	37,029	34.7	2.9	2,957	36.9

SIREP: Sistema Informativo Registri di Esposizione Professionale; NACE: Nomenclature statistique des activités économiques dans la Communauté européenne; ^anumber of firms in SIREP; ^bpercentage of firms in SIREP with respect to the latest industry census data; ^cnumber of workers reported by firms (exposed+non-exposed) in SIREP; ^dpercentage of workers reported by firms in SIREP with respect to the latest industry census data; ^epercentage of exposed workers with respect to non-exposed workers reported by firms in SIREP; ^festimated number of potentially exposed workers.

the information collected in SIREP will help us understand how the implementation of new EU regulations on the protection of workers' health from carcinogenic risks influences the application of primary prevention in the workplace, both in terms of reducing exposure levels and the number of exposed individuals.

Limitations and strengths

The heterogeneous territorial coverage and the limited representativeness in some economic activities are the two main limitations of the SIREP database, as already underlined in the previous study [7]. Activity sectors and workers occupations are represented differently within the SIREP database. Exposure measurements in some sectors and/or occupations, known to be at risk of formaldehyde exposure, appear to be poorly represented (e.g., construction where it is used in form of resins or adhesives, manufacture of textiles where it is used as a fixing and anti-creasing agent) [3]. Moreover, potential underreporting in less regulated sectors and in small and medium-sized enterprises (SMEs) could also have an impact, as these settings often lack systematic monitoring and may not report exposures as rigorously as larger, more controlled industries. The possibility that firms that do not record or report exposure data have higher exposure levels may have influenced our estimates. Uncertainty may also have been introduced due to differences in air sampling, analytical procedures, sample collection methods (personal or stationary) and data classification. For these reasons, to increase the precision of estimates, only sectors and occupations having more than 50 measurements recorded were included in the statistical analysis. Finally, only the sectors better characterized in SIREP were considered to estimate the number of workers potentially exposed. As a consequence of this selection, certain activity sectors were excluded due to limited information on the size of the reported workforce (e.g., manufacture of textile). The robustness of the estimate for each selected sector depends on how many firms and workers registered in SIREP match those recorded in the ISTAT national census. Higher percentages of firms (column three of *Table 4*) and workers (column five of *Table 4*) in SIREP indicate greater reliability of the estimate. Lastly, the number of exposed workers in each sector was calculated assuming the same ratio of exposed to non-exposed workers in firms reporting and not reporting exposure data to SIREP, which could lead to a possible over- or under-rating of the estimated percentage of potentially exposed workers. The main challenges in accurately assessing formaldehyde exposure and risk arise from insufficient sector-specific data, particularly in textiles and construction,

where widespread exposure is expected but systematic monitoring appears to be lacking. Inadequate reporting and inconsistent monitoring protocols further hinder reliable assessment of exposure risk. The uncertainties identified in this study are likely to contribute to a moderate or severe underestimation of actual exposure. Insufficient sector-specific data and incomplete reporting/notification are the most severe, while lack of standardized monitoring protocols and workplace practice variability have a moderate impact on the possible underestimation. To refine the evaluation of the data presented in this study, corrective actions could include harmonising measurement methodologies and increasing the frequency and coverage of monitoring, particularly in SMEs and sectors with historically lower oversight. It is also recommended to standardize reporting systems and provide targeted training for both employers and workers on exposure recognition and reporting procedures.

CONCLUSIONS

In summary, this study confirms that formaldehyde exposure remains a key occupational health issue in Italy, particularly in healthcare, laboratory, and manufacturing sectors. The results underscore the need for stronger preventive measures, improved monitoring and reporting, and consistent regulation. Addressing uncertainties, such as exposure variability and data underreporting, will require more detailed risk assessments and focused research to better safeguard workers' health and guide policy. The estimates here realized can be useful for conducting sector- and occupation-specific surveys, confirming the SIREP information system on occupational exposure as a precious source of data. The inclusion of formaldehyde under the Directive n. 2004/37/EC, on the protection of workers from the risks related to exposure to carcinogens, as expected, has significantly improved the reporting system, allowing for better mapping and identification of work situations most at risk of exposure.

Conflict of interest statement

The Authors declare that they have no competing interests.

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