Air Quality, Atmosphere & Health (2024) 17:877–890
https://doi.org/10.1007/s11869-023-01471-5

Effective mitigation strategies for reducing workers' exposure to formaldehyde: a systematic review

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Received: 14 July 2023 / Accepted: 7 November 2023 / Published online: 23 November 2023

Abstract

Formaldehyde is a toxic and carcinogenic compound, still used in several occupational settings due to its properties. Thus, in these working scenarios, it is necessary to provide effective measures to reduce workers' exposure to formaldehyde. The aim of this systematic review is to provide a picture of the worldwide mitigation strategies implemented in occupational environments for minimizing the exposure to formaldehyde and which ones are the most effective for this purpose.

The systematic review was performed according to PRISMA statement; the protocol was registered in PROSPERO (CRD42022302207). The search was performed on three electronic databases (PubMed, Scopus, and Web of Science). Studies were considered eligible if they describe strategies for mitigating formaldehyde occupational exposure and their efficacy. We included articles reporting observational studies, semi-experimental, and experimental studies and published in the English language, from the inception to March 26th, 2023. The quality assessment was performed using the Newcastle–Ottawa Quality Assessment Scale.

In total, 28 articles were included in the review. The employment scenarios/activities studied were human and veterinary anatomy, autopsy, histopathology or pathology laboratories, embalming procedures, hospital, operating theaters, aquaculture, textile or foundry industries, industry using 3-D printers, offices, and firefighters' activities. Different methods have proven useful in mitigating formaldehyde exposure, such as the use of personal protective equipment, engineering control methods, organization methods, and technical strategies, with a reduction of airborne formaldehyde until to 99.6%. The highest reduction was obtained in an anatomy laboratory through locally exhausted dissection tables equipped with activated carbon filters. The specific suitable procedures should be standardized and applied in all work settings for an appropriate risk management, in order to protect the health of exposed workers.

Keywords Formaldehyde · Occupational settings · Strategies for mitigating exposure · Systematic review as a topic

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Introduction

Main characteristics of formaldehyde

Formaldehyde (FA) is a natural substance both present in the environment and in the human body. In the environment, it is a colorless, strong-smelling gas that rapidly biodegrades in air, water, and soil under both aerobic and anaerobic conditions. It can also be manufactured as a liquid (formalin) or a solid (paraformaldehyde) (Dubey and Das 2021). FA is one in a large family of chemical compounds called volatile organic compounds (VOCs). Those substances are emitted by a wide range of products called "releasers" (David and Niculescu 2021). FA is usually present at low levels, even less than 0.03 parts per million (ppm), in both outdoor and indoor air. The rate at which FA is released is accelerated by heat and may also depend on the level of environmental humidity (National Cancer Institute 2011). Residences or offices that contain FA releasers can present airborne levels greater than 0.03 ppm, even up to ten times higher than outdoors (Trocquet et al. 2023; Paciência et al. 2016).

Formaldehyde in occupational settings

FA is widespread in many working settings, with different levels for different occupations (Cammalleri et al. 2022). A very recent systematic review reported that the highest FA concentrations in occupational settings were observed in waterpipe cafes (1620 μg m^{-3}) and anatomy and pathology laboratories (4237.5 μg m^{-3}) (Khoshakhlagh et al. 2023). The primary sources of occupational exposure to FA are industrial production (resins, molding compounds, fertilizer, paper, wood products, furniture, laminates, plastics, pesticides, chemical manufacture, rubber, leather tanning, iron foundries, photographic film, textiles, scientific supply, sanitisers, and cosmetics), agri-food sector (sugar production, grain, and seed preservation), embalming procedures, healthcare setting (preserved tissue and specimens), building (manufactured wood products), transportation and fuel (product of combustion of automobiles, refineries, and power plants) (Cammalleri et al. 2022).

Adverse effects for human health determined by formaldehyde exposure

FA exposure (mainly by inhalation) may potentially cause a variety of symptoms and adverse health effects. Acute exposure can cause irritation to the eye, nose, throat, and skin, coughing, wheezing, and allergic reactions (WHO 2009). Some people, like those who suffer from asthma, may be more sensitive to the effects of inhaled FA (Wolkoff and Nielsen 2010). At very high concentrations, FA can cause pulmonary edema and can result in death (Dubey and Das 2021). Long-term exposure to high levels of FA has been associated with cancer both in humans and animals (Protano et al. 2021). In 2006, the International Agency for Research on Cancer (IARC) changed its classification from Group 2A (probable human carcinogen) to Group 1 (carcinogenic to humans) (IARC 2006). This change was based on "sufficient evidence of nasopharyngeal cancer in humans, strong but not sufficient evidence of leukemia in humans, and limited evidence of sinonasal cancer in humans." In 2009, IARC reaffirmed the Group 1 classification and also concluded that there was sufficient evidence of leukemia in humans (Baan et al. 2009), even if a very recent systematic review does not fully support this evidence (Protano et al. 2021).

Policies for reducing formaldehyde pollution in workplaces

Given the health implications of FA exposure, it is recommended to put in place all the possible policies for reducing FA pollution in workplaces. In 2009, the World Health Organization (WHO) established an indoor air quality guideline for short- and long-term exposures to FA equal to 0.08 ppm for all 30-min periods at lifelong exposure (WHO 2009). According to the Occupational Safety and Health Administration (OSHA) Formaldehyde standard (29 CFR. 1910.1048), employers must not allow employees to be exposed to levels of FA that exceed the permissible exposure limit (PEL) of 0.75 ppm on an 8-h time-weighted average (TWA) or the short-term exposure limit (STEL) of 2 ppm in 15 min. The American Conference of Governmental Industrial Hygienists (ACGIH) in 2017 stated that the threshold limit value of FA is 0.1 ppm (TWA) and 0.3 ppm (STEL) to minimize potential sensory irritation (ACGIH 2017). Whatever the exposure limit is taken into consideration, FA concentration must be kept as low as possible to protect worker's health. As stated, years ago, by The California Air Resources Board, "…the most effective way to reduce formaldehyde in indoor air is to remove or reduce sources of formaldehyde… …and avoid adding new sources" (CARB 2004). There are several known approaches for lowering the concentration of FA in indoor environments. They include removal of the source, surface coating, fumigation with ammonia, increased ventilation, catalytic reactions, and adsorption. In addition, if it is not possible to reduce the exposure to FA below the PELs, employers must provide workers with appropriate personal protective equipment (PPE), such as respirators and gloves (OSHA 2023). They should also provide medical surveillance for all workers exposed to FA at concentrations at or above the action level or exceeding the STEL. Given the relevance of the health risks, several research has been performed for developing further mitigation strategies.

Objective of the review

The aim of this systematic review is to provide a picture of the worldwide mitigation strategies implemented in occupational environments for minimizing the exposure to FA and which ones are the most effective for this purpose.

Materials and methods

Search strategy and selection procedures

This systematic review was carried out according to the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines (Page et al. 2021), and the protocol was registered in PROSPERO (reference number CRD42022302207). The search was performed on three electronic databases (PubMed, Scopus, and Web of Science). In particular, the search on PubMed was performed by title, abstract, and MeSH terms; the search on Scopus and Web of Science included topic by title, abstract, and keywords. The search was carried out from March 16th, 2023 to March 26th, 2023.

PICOS statement

PICOS framework was used to frame the review question as follows: (a) population, workers professionally exposed to FA; (b) intervention, FA exposure mitigation in the workplace; (c) comparison, age-, gender-, and workplace scenario–matched control group (if present); (d) outcome, identification of all the strategies and techniques for mitigating FA exposure in the workplace and the best interventions among them; (e) study, observational studies and semi-experimental and experimental studies. The PICOS criteria are summarized in Table 1.

Inclusion and exclusion criteria

This systematic review was focused on the mitigation of FA occupational exposure to protect workers exposed in workplaces. Consequently, studies were considered eligible if they describe strategies and/or techniques for mitigating FA exposure in the studied scenarios and if they report an evaluation of the efficacy of the strategies and techniques used. Reviews, meta-analysis, case studies, proceedings, qualitative studies, editorials, commentary studies, and any other type of articles not reporting original data were excluded. However, references to critical and systematic reviews and meta-analyses were examined to identify further articles in this field. We included only articles published in the English language, from the inception to March 26th, 2023. Titles and abstracts acquired from the three databases were

Table 1 PICOS criteria for the systematic review

	P (population)	I (intervention)	C (comparison)	O (outcome)	S (study)
Included	Workers professionally exposed to formaldehyde	Formaldehyde exposure mitigation in the workplace	Age-, gender- and workplace scenario–matched control group (if present)	Identification of all the strategies and techniques for mitigating formaldehyde exposure in the workplace and the best interventions among them	Observational studies, semi-experimental and experimental studies
Excluded	Individuals exposed to formaldehyde in non-occupational settings	No intervention to mitigate formaldehyde exposure in the workplace			Reviews, meta-analysis, case studies, proceedings, qualitative studies, editorials, commentary studies, and any other type of articles not reporting original data were excluded

transferred to Zotero Software, and titles in other languages and duplicates were excluded. Five authors (IP, LC, GDA, FC, CP) independently carried out the screening to identify the potentially eligible studies by title and abstract, following the inclusion criteria mentioned before. In the successive step, full texts were read independently by the same five authors (IP, LC, GDA, FC, CP) and consensus among the authors achieved all the disagreements.

Data extraction process and quality assessment

Bibliographic information like author, year, country, type of study, employment scenarios, mitigation strategy, and specific mitigation systems, evaluation method, pre- and post-mitigation values, and main results was summarized. The quality assessment was performed by the use of the tool NOS—Newcastle–Ottawa Quality Assessment Scale—adapted from cohort case–control and cross-sectional studies to perform a quality assessment for the included studies. The scale includes three sections: (1) selection, consisting of three questions; (2) comparability, consisting of one question; (3) outcome, consisting, respectively, of two questions for cross-sectional studies and three questions for cohort and case–control studies. According to the NOS scale, an overall rating of "good," "fair," or "poor" "quality was assigned to all the included papers, as follows: good if the NOS score was 7 to 9, fair if the NOS score was 4 to 6, and poor if it was 0 to 3 (Palmieri et al. 2016).

Five authors (IP, LC, GDA, FC, CP) assigned a score to all studies independently, and conflicts between the authors were discussed and resolved.

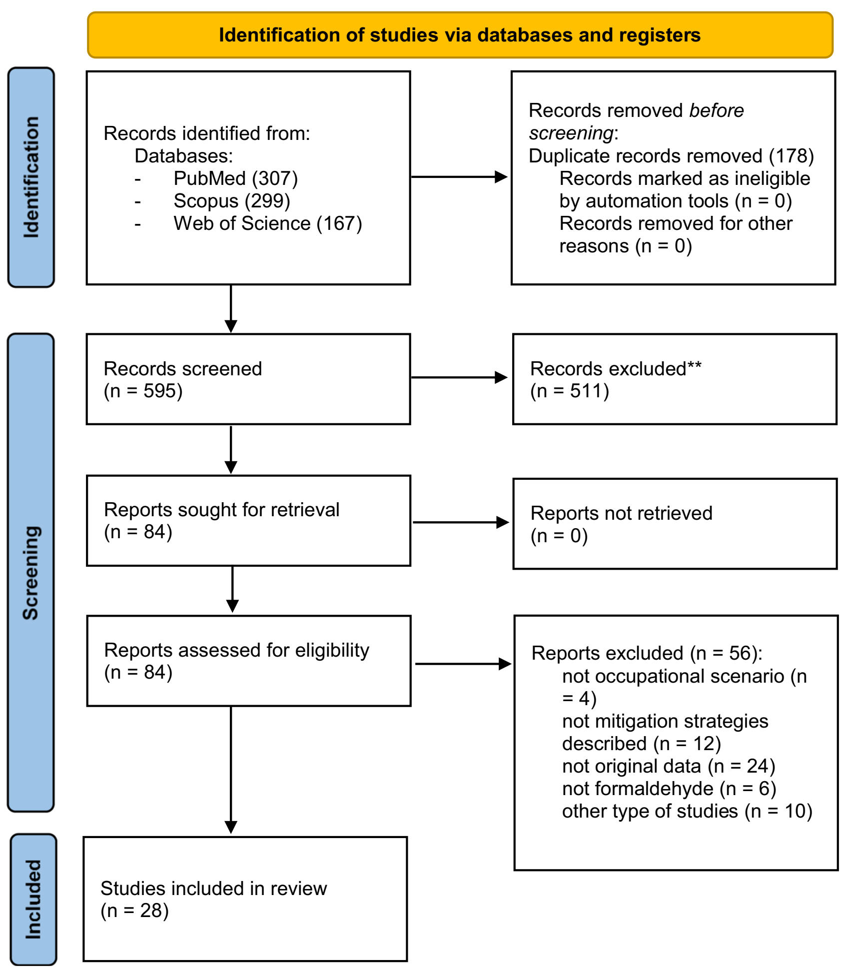
Results

Article selection

Figure 1 shows the flow chart of the review.

In total, 773 records were found and, after removing duplicates, 595 were screened for inclusion and 84 were evaluated for eligibility. After reading the full text, 56 articles were excluded. In particular, 4 articles were excluded because the studies were not performed in occupational scenarios, 12 articles because they did not describe mitigation

Fig. 1 PRISMA flow diagram of the literature search



strategies, 24 articles because they did not provide original data, and 10 articles because they presented case reports or review. After the screening process, 28 articles met the inclusion criteria and were included in the review.

Tables 2, 3, and 4 show the selected characteristics of the studies included in the systematic review and the efficiency of different mitigation systems, expressed as reduction %, in different employment scenarios. In particular, Table 2 reports data for healthcare and research settings, Table 3 for industrial scenarios, and Table 4 for firefighters' and other settings. Unless otherwise specified, all the pre- and post-mitigation values presented in Tables 2, 3, and 4 are expressed in mg m^{-3}.

Main characteristics of the studies performed in healthcare and research settings

Table 2 shows the characteristics of the studies included carried out in healthcare and research settings. In total, 20 articles out of a total of 28 included were focused on healthcare and research settings, published from 1984 (Edwards and Cambell 1984) to 2021 (Fustinoni et al. 2021).

One of the best mitigation systems adopted to reduce FA concentration for workers occupationally exposed during anatomy, autopsy, or embalming procedures (e.g., embalmers, pathologist, medical examiner) was the use of locally exhausted dissection tables (Ohmichi et al. 2007; Yamato et al. 2005; Coleman et al. 1995; reduction percentage between 77.3 and 99.6%). In particular, the efficiency was higher when the dissection table was equipped with activated carbon filters (Coleman et al. 1995; reduction percentage equal to 99.6%) and lower when the dissection table was equipped with a photocatalytic device able to degrade FA (Ohmichi et al. 2007; reduction percentage equal to 77.3%). Another approach adopted to reduce FA concentration during autopsy or embalming activities was the improvement of the ventilation system. This mitigation approach guaranteed a reduction of airborne FA between 69.5 and 91.7% (Pfeil et al. 2020; Scheepers et al 2018; Gressel et al. 2001; Hiipakka et al. 2001). In particular, the highest reduction percentage was obtained when the improvement of the ventilation system was combined with the use of a binding agent (Pfeil et al. 2020; reduction percentage: 95.8%). Another mitigation approach was the use of chemicals (e.g., urea and ammonium carbonate) which react with FA to produce less toxic chemicals (Kawata et al. 2019; Kawamata et al. 2004; reduction percentage between 40.9 and 73.9%). On the other hand, the use of air purifying devices (e.g. ozone generator) appeared to have no relevant effect on reducing FA concentration during embalming procedures (Esswein and Boeniger 1994).

In hospitals, specifically in pathology and histopathology laboratories, FA is deliberately used to preserve histologic and pathologic specimens. In those workplaces, the most commonly used mitigation technique was the use of a ventilation system. Edwards and Campbell (1984) reported a reduction percentage of 86.2% of FA due to the installation of an extraction system. This percentage raised up to 88.8–98.1% when the improvement of the ventilation system was combined with a training program to educate local workers and with the use of a negative pressure room (d'Ettorre et al. 2021). Good results were also obtained when the enhancement of the ventilation system was coupled with the use of a vacuum sealing machine and a fume hood computer-based system (Dugheri et al. 2020; reduction percentage: 78–95.4%). Ogawa et al. (2019) reported a lower reduction percentage (56.7%) when the improvement of the ventilation system was combined with workers' training and the use of a video camera and a volatile organic compound detector (Ogawa et al. 2019). The combination of the ventilation system, new procedures, better waste, and solvent management, and the use of half facepiece respirators and of furniture without any pad reported by Fustinoni et al. (2021) resulted in a reduction percentage of airborne FA between − 7.7 and 53.2% (Fustinoni et al. 2021). Data reported by Mäkelä et al. (2003) are not comparable with the others because this work takes into account dermal contact with FA instead of the inhalation route (Mäkelä et al. 2003). The work by Xu and Stewart (2016) did not specify FA concentration before the application of mitigation strategies; for this reason, it was not possible to calculate and compare the reduction percentage of FA (Xu and Stewart 2016).

Also, veterinary doctors are exposed to FA during anatomical studies. In this work environment, the mitigation systems adopted to reduce the airborne concentration of FA are similar to those adopted in anatomy and autopsy laboratories for humans. Nacher et al. (2007) reported that the use of locally exhausted dissection tables led to a 91.6% decrease in airborne FA (Nacher et al. 2007). The use of urea or urea fertilizer solutions was the mitigation system reported by Ninh et al. (2018) able to decrease FA concentration up to 88.4% and 84.4%, respectively (Ninh et al. 2018).

Main characteristics of the studies performed in industrial settings

Table 3 reports the characteristics of the studies included performed in industrial settings.

Four articles included in the review were focused on occupational exposure to FA in industrial scenario, published from 1990 (Luker and Van Houten 1990) to 2022 (Kim et al. 2022). Voorhees and Barnes (2016) studied an aquaculture setting, and they reported that a simple organization method like keeping the door open during egg treatment can reduce airborne FA concentration by up to 25.2% (Voorhees and Barnes 2016). Besides, Luker and Van Houten (1990) studied the textile industry where FA-based

Table 2 Selected characteristics of studies included evaluating mitigation strategies for occupational exposure to formaldehyde (FA, unless otherwise specified, expressed in mg m^{-3}) in health-care and research settings

Employment scene	Author year	Country	Mitigation strategy	Specific mitigation system	Evaluation method	Pre-mitigation value	Post-mitigation value	Reduction %	NOS score
Anatomy laboratory	Coleman 1995	Israel	Technical strategy	Locally exhausted dissection tables equipped with activated carbon filters	Not specified	9.2	0.037	99.6	Fair
	Kawamata and Kodera 2004	Japan	Technical strategy	Use of ammonium carbonate	Detection kit and spectrophotometric analysis	1.84	0.48	73.9	Fair
	Ohmichi et al. 2007	Japan	Technical strategy	Table for gross anatomy equipped with a photocatalytic device	Active sampling and HPLC–UV/DAD analysis	0.44	0.10	77.3	Fair
	Scheepers et al. 2018	The Netherlands	Technical strategy and organization methods	Improving the ventilation system, sample handling, and storage	Active sampling and HPLC–UV/DAD analysis	0.12 0.29	0.029 0.089	76.6 69.5	Good
	Kawata et al. 2019	Japan	Technical strategy	Use of urea solution	Gas detector tubes	1.35 1.69	0.80 0.97	40.9 42.4	Fair
	Pfeil et al. 2020	Germany	Technical strategy	Use of long throw nozzle system Use of long throw nozzle system and FA binding agent	Active sampling and passive sampling and HPLC–UV/DAD analysis	1.01	0.26 0.04	74.8 95.8	Good
Autopsy laboratory	Yamato et al. 2005	Japan	Technical strategy	Locally exhausted dissection tables	Active sampling and HPLC–UV/DAD analysis	0.59	0.061	89.7	Fair
Embalming procedures	Gressel et al 2001	-	Technical strategy	Locally exhaust ventilation system	Not specified	11.1	< 0.92	91.7	Poor
	Hiipakka et al. 2010	Spain	Technical strategy	Locally exhaust ventilation controls	Passive sampling and infrared spectrophotometry	2.38	0.41	82.8	Good
	Esswein and Boeniger 1994	USA	Engineering control methods	Air-purifying devices (ozone generator)	Portable sampler	1.60	1.62	-1.3	Good

Table 2 (continued)

Employment scene	Author year	Country	Mitigation strategy	Specific mitigation system	Evaluation method	Pre-mitigation value	Post-mitigation value	Reduction %	NOS score
Hospital	Mäkelä et al. 2003	Finland	Personal protection equipment/recommendations for minimizing the exposure	Use of different surgical rubber gloves: Biogel© Supersensitive (A), Regent© Surgical (B), Biogel© (C), Biogel© Orthopaedic (D), Biogel© Indicator (E), Biogel© Reveal (F), Skinsense TMN (G)	HPLC–UV/DAD analysis	Not specified	0.5 μg/cm^{-2}/min^{-1} (A) 0.4 μg/cm^{-2}/min^{-1} (B) 0.35 μg/cm^{-2}/min^{-1} (C) 0.2 μg/cm^{-2}/min^{-1} (D) <0.1 μg/cm^{-2}/min^{-1} (E, F, G)		Good
Histopathology laboratory	Edwards and Cambell 1984	UK	Technical strategy	Installation of extraction systems	Infrared gas analysis	≤ 15.96	< 2.21	86.2	Fair
Pathology laboratory	Xu and Stewart 2016	USA	Technical strategy	Use of: canopy (A), recirculating backdraft station (B), slot ventilation (C), ducted backdraft station (D)	Active sampling and GC-FID analysis	Not specified	0.79 (A) 0.74 (B) 0.49 (C) 0.15 (D)		Goof
	Ogawa et al. 2019	Japan	Technical strategy	Staff training, improving ventilation system, intervention with video camera	Portable sampler	0.12	0.052	56.7	Good
	Fustinoni et al. 2021	Italy	Personal protection equipment/recommendations for minimizing the exposure	New procedures and cutters, improving ventilation system, use of furniture without any pad, use of half facepiece respirators, improving waste and solvent management	Passive sampling for environmental and personal monitoring and HPLC–UV/DAD analysis; photoacoustic infrared spectrometry analyzer for continuous environmental monitoring	0.021 0.026 0.047	0.012 0.028 0.022	42.9 -7.7 53.2	Good

Table 2 (continued)

Employment scene	Author year	Country	Mitigation strategy	Specific mitigation system	Evaluation method	Pre-mitigation value	Post-mitigation value	Reduction %	NOS score
	d'Ettorre et al. 2021	Italy	Technical strategy and personal protection equipment/recommendations for minimizing the exposure	Staff training, improving ventilation system, use of negative pressure room	Active sampling and HPLC–UV/DAD analysis	1.67 0.25	0.031 0.028	98.1 88.8	Fair
Pathology laboratory (PL) and operating theater (OT)	Dugheri et al. 2020	Italy	Technical strategy	Use of vacuum sealing of surgical specimens and fume hoods computer-based system	Active sampling and HPLC–UV/DAD analysis	0.613 0.20	0.028 0.044	95.4 78.0	Fair
Veterinary anatomy laboratory	Nacher et al. 2007	Spain	Technical strategy	Locally exhausted dissection tables	Active sampling and chromotropic acid spectrophotometry method	0.44	0.037	91.6	Fair
	Ninh et al. 2018	Thailand	Technical strategy	Use of urea solution	Portable sampler	7.73	0.90	88.4	Fair
				Use of urea fertilizer solution			1.20	84.4	

Table 3 Selected characteristics of studies included evaluating mitigation strategies for occupational exposure to formaldehyde (FA, unless otherwise specified, expressed in mg m^{-3}) in industrial settings

Employment scene	Author year	Country	Mitigation strategy	Specific mitigation system	Evaluation method	Pre-mitigation value	Post-mitigation value	Reduction %	NOS score
Aquaculture	Voorhees and Barnes 2016	USA	Organization methods	Outside door open	Portable sampler	1.51	1.13	25.2	Fair
Textile Industry	Luker and Van Houten 1990	USA	Technical strategy	Use of lower FA fabric	Passive sampling and spectrophotometric analysis	1.01	0.16	84.2	Fair
Foundry Industry	Morteza et al. 2013	Iran	Technical strategy	Locally exhaust ventilation system	Active sampling and GC-FID analysis	28.7	19.03	33.7	Fair
Industry using 3-D printers	Kim et al. 2022	South Korea	Technical strategy	Use of a ventilated enclosure	Active sampling and HPLC–UV/DAD analysis	0.037	0.024	35.1	Fair

resins were used, and they found that the use of fabrics with lower FA content can drastically reduce garment workers' exposure (reduction percentage of 84.2%) (Luker and Van Houten 1990). Also, Morteza et al. (2013) measured FA concentration in a foundry plant before and after the use of a locally exhaust ventilation system, recovering that this mitigation system can lead to a 33.7% of airborne FA reduction (Morteza et al. 2013). Finally, Kim et al. (2022) measured FA concentration in an industry where 3-D printers were used, and using ventilated enclosure as a mitigation strategy, they obtained a 35.1% of FA reduction (Kim et al. 2022).

Main characteristics of the studies performed in firefighters' and other settings

The characteristics of the studies included carried out in firefighters' and other settings are reported in Table 4.

In total, we included four studies focused on firefighters' and two researches performed in other settings (both in offices), published from 2000 (Dingle et al. 2000) to 2021 (Staak et al. 2021).

The most common mitigation system adopted by this class of workers was the use of air-purifying respirators (Staack et al. 2021; Currie et al. 2009; De Vos et al. 2009). For example, Staack et al. (2021) and Currie et al. (2009) reported that the use of air-purifying respirators equipped with chemical, biological, radiological, and nuclear canister and the use of positive pressure self-contained breathing apparatus can guarantee a 90% and 99.9% reduction of airborne FA, respectively (Staack et al. 2021; Currie et al. 2009). Data reported by De Vos et al. (2009) are not comparable with the others because the authors did not report pre-mitigation values, so it is not possible to calculate FA reduction percentage (De Vos et al. 2009). Despite that, post-mitigation values reported by De Vos et al. (2009) are comparable to or higher than those reported by Staack et al. (2021) and Currie et al. (2009) (Staack et al. 2021; Currie et al. 2009; De Vos et al. 2009).

As regards the offices' scenarios, Dingle et al. (2000) reported that the placement of 20 plants in the office environment can decrease FA airborne concentration up to 10.5% (Dingle et al. 2000). A smaller reduction of FA (2.3%) was obtained by Zayed et al. (2017) by placing 3 corn cane plants in an office (Zayed et al. 2017).

Discussion

FA is a chemical substance deliberately used in several work environments as a disinfectant and as a fixative for human and animal corpses. In 2006, IARC classified FA as carcinogenic to humans (Group 1) (IARC 2006), but due to its high disinfectant and preservative properties, the use of this gas is the only valid system for treating materials that cannot be treated by heat or steam and for long-term storage of cadavers and anatomical specimens (Cammalleri et al. 2022). Since replacing FA is rather difficult, the available literature from 1984 to 2022 was investigated to compare the mitigation systems adopted to reduce airborne FA concentration in different work environments. Indeed, when replacing or eliminating dangerous chemicals is not possible, several preventive/protective measures can be undertaken, such as

Table 4 Selected characteristics of studies included evaluating mitigation strategies for occupational exposure to formaldehyde (FA, unless otherwise specified, expressed in mg m^{-3}) in firefighters' and other settings

Employment scene	Author year	Country	Mitigation strategy	Specific Mitigation system	Evaluation method	Pre-mitigation value	Post-mitigation value	Reduction %	NOS score
Firefighters	De Vos et al. 2008	Australia	Personal Protection Equipment/ Recommendations for Minimizing the Exposure	Use of: particulate filters (A), particulate/organic vapor filters (B), particulate/organic vapor/formaldehyde filters (C)	Active sampling and HPLC–UV/DAD analysis	Not specified	0.25 (A) 0.021 (B) 0.017 (C)		Good
	Currie et al. 2009	USA	Personal Protection Equipment/ Recommendations for Minimizing the Exposure	Air-purifying respirators	Active sampling and GC-NPD analysis	> 0.37	< 0.037	90.0	Fair
	Staack et al. 2021	USA	Personal Protection Equipment/ Recommendations for Minimizing the Exposure	Air-purifying respirators with: chemical, biological, radiological, and nuclear canister (A), positive pressure self-contained breathing apparatus (B)	Active sampling and HPLC–UV/DAD analysis	0.63	< LOD (A,B)	99.9	Good
Office	Dingle et al. 2000	Australia	Personal Protection Equipment/ Recommendations for Minimizing the Exposure	Use of twenty plants	Passive sampling and HPLC–UV/DAD analysis	1.05	0.94	10.5	Fair
	Zayed et al. 2017	United Arab Emirates	Personal Protection Equipment/ Recommendations for Minimizing the Exposure	Use of three Corn Cane plant	Portable sampler	0.088	0.086	2.3	Poor

isolation of activities at higher emissions, improvement, implementation, and optimization of collection systems at the source, adoption of new general standard operative procedures for reducing the exposure, identification, and purchase of PPE. These measures, together with the training and update on chemical risks knowledge, are very useful activities to control the chemical threat in occupational setting (Fustinoni et al. 2021).

Formaldehyde mitigation strategies in healthcare and research settings

The most studied occupational scenarios by the articles included in the review involved healthcare and research settings. In these cases, the main mitigation approach tested for minimizing occupational FA exposure was represented by technical strategies, but also, other systems were studied, such as organization methods, engineering control methods, personal protection equipment, and recommendations for minimizing the exposure.

Almost all studies found a reduction of airborne levels of FA after the application of one or more mitigation strategies, ranging from 42.9% (Fustinoni et al 2021) to 99.6% (Coleman 1995). In particular, the highest reduction levels were achieved in a human anatomy laboratory by the use of locally exhausted dissection tables equipped with activated carbon filters (Coleman 1995). Conversely, in one case (Fustinoni et al. 2021), the authors recovered higher levels of FA after the introduction of new procedures and cutters, improvement of the ventilation system, use of furniture without any pad, use of half facepiece respirators, and improvement of waste and solvent management. However, the pre- and post-mitigation values were very similar resulting, respectively, 0.026 and 0.028 mg m^{-1} (Fustinoni et al. 2021); thus, it is presumable that differences were casual, and the tests should be repeated to confirm or disprove this finding.

Formaldehyde mitigation strategies in industrial settings

FA was often used or produced in industrial setting and, thus, also in this kind of occupational scenario, it is essential to minimize workers' exposure to FA. For example, FA-based resins are used in the textile industries to reduce wrinkle formation in fabrics, or in the foundry industry, they are used as constituent of binders for the hot box process. Besides, in aquaculture occupations settings FA is deliberately used to prevent and treat molds during egg incubation. In addition, airborne FA can be present in industries and other settings using the 3-D printers, because these devices use acrylonitrile–butadiene–styrene copolymers, which are well-known emitters of volatile organic compounds, including FA. All these scenarios were studied by the articles included (Luker and Van Houten 1990; Kim et al. 2022; Morteza et al. 2013; Voorhees and Barnes 2016), and all the mitigation strategies applied were useful to reduce airborne level of FA. In particular, the best approach to reduce FA concentration was a technical strategy involving the use of fabrics with lower FA content. As it is obvious, this result highlights that the elimination or the reduction of the contaminant at its source remains the most effective way to minimize the exposure.

Formaldehyde mitigation strategies in firefighters' and other settings

Further occupational activities that are at risk of FA exposure are those carried out by firefighters and office workers. Indeed, firefighters are workers exposed to combustion products, including FA, and office environments, due to the presence of emitting materials, are often affected by FA contamination.

As regards firefighters, one of the few possibilities to reduce FA exposure is the use of personal protective equipment, and all the studies included (De Vos et al. 2008; Currie et al. 2009; Staack et al. 2021) demonstrated that this kind of strategy is effective for protecting workers.

Regarding the offices, the two studies included in the review applied the same approach, placing some plants in the monitored offices, and they obtained a reduction, even if modest, of airborne FA (Dingle et al. 2000; Zayed et al. 2017). This result is in line with those recovered previously for other VOCs (Bhargava et al. 2021), while it is in contrast with the findings reported by a critical review on this issue (Cummings and Waring 2020). Probably, this disagreement is determined by differences in plant species and their specific mechanism of action. Given the importance of reducing the airborne levels of indoor contaminants, including FA, the use of plants should be studied in depth to understand which species are suitable for this purpose.

Main limitations of the systematic review

The present systematic review has some limitations. Firstly, the approaches for minimizing the exposure to FA and the modality used to evaluate the mitigation in the studied occupational settings were different and, thus, comparing the results of the articles is very hard. Besides, the heterogeneity of the studies included in the review did not allow us to perform a meta-analysis of the results of the single studies. However, to our knowledge, this is the first study that systematically reviews the literature on approaches to mitigate exposure to FA, giving a picture of all the strategies available and their effectiveness in reducing exposure.

Conclusions

The results of this systematic review demonstrate that all the mitigation strategies and techniques evaluated are effective in reducing workers' exposure to FA. The identification of effective mitigation strategies is of great importance for protecting workers from exposure to FA, especially considering that this substance is a carcinogen. Indeed, the main prevention strategy for FA is its elimination from the workplace and its replacement with a non-carcinogenic analogue, but this cannot be implemented in several scenarios because in several cases, FA is irreplaceable. Thus, different strategies for mitigating FA exposure have been implemented and evaluated, based on types of activities, working methods, and related environments. In particular, the following approaches have been successfully used: the use of PPE, engineering control methods, and organizational and technical strategies. Our findings could be useful to provide a scientific support to the risk management process, in order to identify the most suitable mitigation strategies for each specific occupational setting.

Author contribution FC was involved in data curation, formal analysis, methodology, investigation, validation, and writing the original draft. MV was involved in conceptualization, data curation, funding acquisition, methodology, project administration, resources, supervision, visualization, and writing—review and editing. AA was involved in data curation, formal analysis, methodology, investigation, and writing the original draft. LC, GDA, and IP were involved in data curation, formal analysis, investigation, and writing the original draft. MP and CLU were involved in validation and writing—review and editing. CP was involved in conceptualization, project administration, validation, writing the original draft, and writing—review and editing.

Funding Open access funding provided by Università degli Studi di Roma La Sapienza within the CRUI-CARE Agreement. This work was carried out within the BRiC-2018 research projects financially supported by Istituto Nazionale Assicurazione Infortuni sul Lavoro (INAIL, Project number B86C19000070001).

Data availability Data have been provided as tables directly within the manuscript, and raw data are available via e-mail upon request from the corresponding authors.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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