DOI: 10.7251/QOL2601046S **UDC:** 546.97+546.94]:547.587.51
Original scientific paper

Assessment of Chemical Hazards in Hospital Workplaces during the Summer Period

Srđan Šabić, Predrag Ilić
PSRI Institute for protection and ecology of the Republic of Srpska, Banja Luka, Banja Luka, Republic of Srpska, Bosnia and Herzegovina, srdjan.sabic@institutzei.net, predrag.ilic@institutzei.net

Abstract: Workplace exposure to gaseous chemical pollutants represents a significant occupational health concern in healthcare environments, particularly in large clinical centers where diverse chemical agents are used and emitted. In this study, we provide a comprehensive assessment of chemical hazards in selected workplaces at the Public University Clinical Center of the Republic of Srpska in Banja Luka during the summer period. The results indicate pervasive exceedances of regulatory reference values for acrolein (C_3H_4O) and localized exceedances for nitrogen dioxide (NO_2), suggesting potential occupational relevance in specific areas. Exploratory factor analysis identified six components explaining approximately 79% of the total variance, indicating multiple partially overlapping emission sources. Correlation analysis revealed structured associations among several reactive and aromatic pollutants, pointing to common controlling processes. Differences between operating rooms and other areas were statistically significant for CO_2, CH_4, isopropanol (C_3H_8O), and acetone ($(CH_3)_2CO$). The findings highlight the spatial heterogeneity and activity-driven nature of chemical exposure in hospital environments and support the need for integrated monitoring approaches to improve occupational health risk management. The study contributes to a better understanding of chemical exposure patterns in hospital environments and provides a basis for future risk management and occupational health interventions.

Keywords: Workplace air quality; FTIR gas analysis; hospital environment; chemical exposure; PCA; occupational health; volatile organic compounds; indoor air pollution.

INTRODUCTION

Air quality at workplaces represents a central occupational-health concern because inhalation exposure provides a direct pathway for both acute and long-term health effects. In work environments characterized by the simultaneous use of multiple chemical products, airborne exposure is rarely limited to a single substance. Instead, workers are typically exposed to complex mixtures whose composition and intensity depend on specific activities, ventilation performance, and temporal dynamics. As highlighted in recent exposure-assessment research, short-term concentration peaks may contribute disproportionately to overall health risk, even when longer-term average concentrations appear moderate (Sabic et al., 2024).

Hospital workplaces constitute a particularly complex indoor environment from an occupational-hygiene perspective. Unlike settings dominated by a single industrial process, hospitals combine medical, laboratory, technical, and service-related activities within the same building envelope. Cleaning and disinfection procedures, clinical and laboratory work, building operation, and outdoor air infiltration occur concurrently, creating spatially and temporally heterogeneous exposure conditions for healthcare workers (Ilić et al., 2018; Božić et al., 2019). As a result, airborne chemical mixtures in hospitals may include both inorganic gases and volatile organic compounds (VOCs), originating from multiple sources that vary by department and task (Becker and Rosenberg, 2008; Fazlzadeh et al., 2015).

Although ambient air pollution has been extensively investigated, indoor air quality in hospital environments requires particular attention because exposures may be intensified by variable ventilation efficiency, episodic emission events, and continuous occupancy. Previous studies have shown that concentrations of

commonly monitored pollutants, such as carbon dioxide (CO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), formaldehyde, and VOCs, can vary substantially between hospital departments and over time. These variations reflect differences in activity patterns, chemical usage, and ventilation performance, and they may be further influenced by seasonal operating conditions (Ilić, 2015; Ilić et al., 2020; Riveron et al., 2023; Loureiro et al., 2025). Importantly, short-term concentration peaks associated with specific tasks—such as intensified cleaning or the handling of solvents—may occur even when average levels remain relatively low, underscoring the need for monitoring approaches capable of capturing temporal variability.

From an occupational-health standpoint, hospital workers represent heterogeneous exposure groups. Environmental services personnel, laboratory staff, clinical workers, and technical or maintenance employees may experience distinct exposure profiles depending on their tasks and work locations. Moreover, combined exposure to multiple airborne chemicals can result in additive, synergistic, or antagonistic effects that cannot be reliably predicted by considering individual substances in isolation (Mehmood et al., 2025). Despite this complexity, chemical exposure in healthcare settings remains insufficiently characterized relative to its importance for worker protection, particularly for support and technical staff who are often underrepresented in routine monitoring programs (Betancur et al., 2024).

FTIR spectroscopy enables simultaneous detection of multiple gaseous pollutants without preseparation, providing time-resolved exposure profiles. Although FTIR spectroscopy enables simultaneous multi-component screening, the technique is inherently based on spectral pattern recognition and may be susceptible to partial band overlap among oxygenated volatile organic compounds (e.g., alcohols and aldehydes). Therefore, careful interpretation of individual compound identification, particularly for reactive carbonyl species such as acrolein, is necessary when evaluating occupational exposure data.

In the Republic of Srpska and the wider Western Balkan region, several investigations have demonstrated the feasibility of measuring multiple chemical hazards in hospital environments and applying multivariate statistical methods to explore co-variation and potential common sources (Ilić et al., 2020). Nevertheless, systematic real-time assessments of multiple gaseous pollutants in large clinical centers remain limited. This gap is particularly evident for the summer period, when ventilation regimes, temperature-dependent emissions, and operational patterns may differ substantially from those observed during other seasons.

The present study was therefore conducted to address this gap by assessing airborne chemical hazards in selected workplaces at the Public University Clinical Center of the Republic of Srpska in Banja Luka during the summer period. Study provides a multi-component examination of exposure to gaseous chemicals in a real-time indoor hospital environment, using FTIR spectroscopy in combination with multivariate statistics. The novelty of the work lies in the integration of (i) on-site FTIR screening of multiple volatile compounds and (ii) pattern identification based on PCA to investigate potential common emission/source footprints in the context of a regional hospital in the Balkans, where such systematic real-time multi-compound exposure screening is rarely reported. Furthermore, the study highlights an applied comparison between operating theatres and other hospital areas under summer working conditions, which can influence ventilation regimes and thus exposure patterns.

MATERIALS AND METHODS

The monitoring campaign was conducted during the summer period (June 2024). Measurements were performed using a portable real-time FTIR gas analyzer operating in direct sampling mode.

A total of N = 58 indoor locations were assessed within the hospital facility. These included:

- 6 operating rooms (OR)

- 52 non-operating areas (other clinical and service rooms)

Each location represents one defined sampling point. At each location, continuous real-time FTIR measurements were performed for 5 minutes, with spectral acquisition every 30 seconds, resulting in 3000 (Acquisition / spectral range: 900–4200 cm^{-1}, spectral resolution: 8 cm^{-1}, acquisition rate: 10 spectra/s) individual spectra per location.

Concentrations of selected gaseous chemical substances in air were measured using a portable multicomponent Fourier Transform Infrared (FTIR) gas analyser Gasmet™ DX 4030 (Gasmet Technologies Oy, Finland; model DX 4030, instrument ID: 091594). The instrument belongs to the Gasmet DX4030 family of portable FTIR analysers, which are designed for simultaneous, real-time detection of multiple inorganic gases and volatile organic compounds (VOCs) in complex air matrices without prior sample preparation or preconcentration. The use of portable FTIR systems in occupational and environmental air quality studies has been widely documented in previous research on indoor air pollution, workplace exposure, and ambient air monitoring.

Ambient air was drawn directly into the analyser using the instrument's built-in sampling pump through a particulate filter mounted at the inlet to prevent dust and aerosols from entering the optical cell. No chemical derivatisation, adsorption, or thermal desorption was applied prior to analysis. This direct sampling approach enabled continuous, in situ measurements of gas-phase concentrations under real working conditions.

The analyser provided validated multigas results within less than 30 seconds per measurement cycle, which allowed high temporal resolution monitoring of concentration fluctuations associated with specific activities or ventilation changes. The sample flow rate was maintained at a constant level recommended by the manufacturer to ensure stable spectral acquisition and reproducible quantification. To ensure interpretability of inter-area comparisons, OR and non-OR locations were sampled within the same campaign window. It should be noted that because measurements were conducted sequentially across locations rather than simultaneously, temporal variability during the day may influence comparisons. This limitation is acknowledged in the Discussion.

Statistical analysis, treatment of Non-Detects and Missing Values

In the original dataset, concentrations reported as "–" represent values below the instrument detection limit (<LOD). These were not treated as zero concentrations.

For descriptive statistics, non-detect values were handled as censored data. For multivariate statistical analysis (correlation and PCA), missing values were treated using median imputation per compound, in order to avoid artificial variance inflation associated with zero substitution.

Zero replacement was avoided because it can bias variance structure and artificially inflate explained variance in PCA models.

Descriptive statistics were calculated for each compound, including mean, median, standard deviation, variance, skewness, and kurtosis. Exceedance frequency was computed relative to the occupational reference limits where available.

Pearson correlation coefficients were calculated using pairwise deletion. PCA was conducted on standardized variables (z-score) after median imputation of <LOD values. The number of retained principal components was evaluated using the Kaiser criterion (eigenvalue > 1) and inspection of the scree plot.

Pearson correlation coefficients were calculated to assess relationships between measured chemical species. A significance threshold of $p < 0.05$ was adopted, and Benjamini–Hochberg correction was applied to control for multiple comparisons.

To evaluate differences between operating rooms and other areas, Welch's t-test was conducted for each chemical species, followed by false discovery rate adjustment. Statistical analyses were performed using Python-based data science libraries.

RESULTS

For consistency throughout the Results section, the following chemical species were included in the analysis:

Carbon dioxide (CO_2); Carbon monoxide (CO); Nitrous oxide (N_2O); Methane (CH_4); Nitrogen dioxide (NO_2); Sulfur dioxide (SO_2); Acetaldehyde (C_2H_4O); Acetone (C_3H_6O); Formaldehyde (CH_2O); Benzene (C_6H_6); Toluene (C_7H_8); m-Xylene (C_8H_{10}); Isopropanol (C_3H_8O); Anhydrous ammonia (NH_3); Acrolein (C_3H_4O); Ethyl acetate ($C_4H_8O_2$); Phenol (C_6H_6O); Pyridine (C_5H_5N); Carbon disulfide (CS_2); Trichloroethylene (C_2HCl_3); Styrene (C_8H_8); Hydrogen chloride (HCl); Methanol (CH_3OH); and Ethanol (C_2H_5OH). This selection reflects substances commonly encountered in hospital indoor air as a result of cleaning and disinfection practices, laboratory activities, technical processes, and ventilation-related influences.

Descriptive statistics across the 58 locations are summarized in Table 1. Skewness and kurtosis values indicate that several compounds show highly right-skewed distributions, consistent with episodic emission events and heterogeneous indoor microenvironments.

Exceedance analysis shows that acrolein (C_3H_4O) exhibits the highest exceedance frequency relative to its reference value, while NO_2 exceedances occur in a smaller fraction of samples. Compounds such as CO_2 and alcohols show elevated levels in selected areas, consistent with occupancy and disinfection-related activities.

Table 1. Descriptive statistics of measured concentrations and number of limit exceedances across sampling locations.

Formula	Limit Values	No	Mean	Median	SD	Variance	Skewness	Kurtosis	Exceed Number	Exceed %
CO_2	5000	58	211	69.9	244	59714	0.78	-1.14	0	0
CO	20	58	0.07	0.01	0.13	0.02	2.74	8.12	0	0
N_2O	50	58	0.55	0.2	1.22	1.49	4.01	17.32	0	0
CH_4	—	58	1.18	0.72	1.17	1.36	0.69	-1.24	0	0
NO_2	0.5	58	1.2	0.11	7.26	52.74	7.59	57.78	12	20.69
SO_2	0.5	58	0.13	0.05	0.19	0.04	2.96	12.74	2	3.45
CH_3CHO	20	58	0.42	0.39	0.28	0.08	1.01	1.26	0	0
$(CH_3)2CO$	500	58	0.25	0.11	0.34	0.11	1.68	2.35	0	0
CH_2O	2	58	0.07	0.06	0.06	0	1.59	3.32	0	0
C_6H_6	1	58	0.5	0.23	1.44	2.08	7	51.51	4	6.9
C_7H_8	50	58	1.13	0.99	1.45	2.09	3.05	11.58	0	0
C_8H_{10}	50	58	0.56	0.03	1.57	2.48	4.27	19.01	0	0
C_3H_8O	400	58	0.53	0.09	0.69	0.47	1.09	-0.03	0	0
NH_3	20	58	0.11	0.03	0.41	0.17	6.11	39.67	0	0
C_3H_4O	0.02	58	1.71	1.5	1.76	3.1	4.09	24.03	57	98.28
$C_4H_8O_2$	200	58	0.31	0.03	0.99	0.98	5.15	26.85	0	0
C_6H_6O	2	58	0.06	0	0.12	0.01	2.69	7.94	0	0
C_5H_5N	5	58	0.71	0	3.08	9.49	7.04	51.76	1	1.72
CS_2	5	58	0.13	0.02	0.52	0.27	7.25	54.09	0	0
C_2HCl_3	10	58	0.03	0.01	0.04	0	2.04	3.43	0	0

C_8H_8	100	58	0.24	0.01	0.49	0.24	2.41	5.23	0	0
HCl	5	58	0.52	0.32	0.88	0.78	6.24	43.79	1	1.72
CH_3OH	200	58	0.16	0	0.38	0.15	3.52	12.83	0	0
C_2H_5OH	1000	58	1.47	0.08	2.3	5.28	1.68	2.09	0	0

[1] Rulebook on Preventive Measures for Safe and Healthy Work during Exposure to Chemical Substances (Official Gazette of the Republic of Srpska, No. 04/20).

Among all measured substances, acrolein (C_3H_4O) clearly emerged as the most critical compound. Concentrations exceeded the applied reference limit at 57 out of 58 sampling locations, corresponding to an exceedance frequency of 98.3%. This pervasive pattern indicates that acrolein represents a systematic exposure concern rather than an isolated anomaly. In contrast, nitrogen dioxide (NO_2) exceeded the corresponding limit at 12 locations (20.7%), while benzene (C_6H_6) exceeded permissible levels at four locations (6.9%). Occasional exceedances were also observed for sulfur dioxide (SO_2) and hydrogen chloride (HCl), suggesting localized or short-term emission events. For the remaining compounds, exceedances were not observed despite occasional elevated values, emphasizing that the primary occupational concern is driven by a limited subset of substances rather than uniformly elevated concentrations across all measured pollutants.

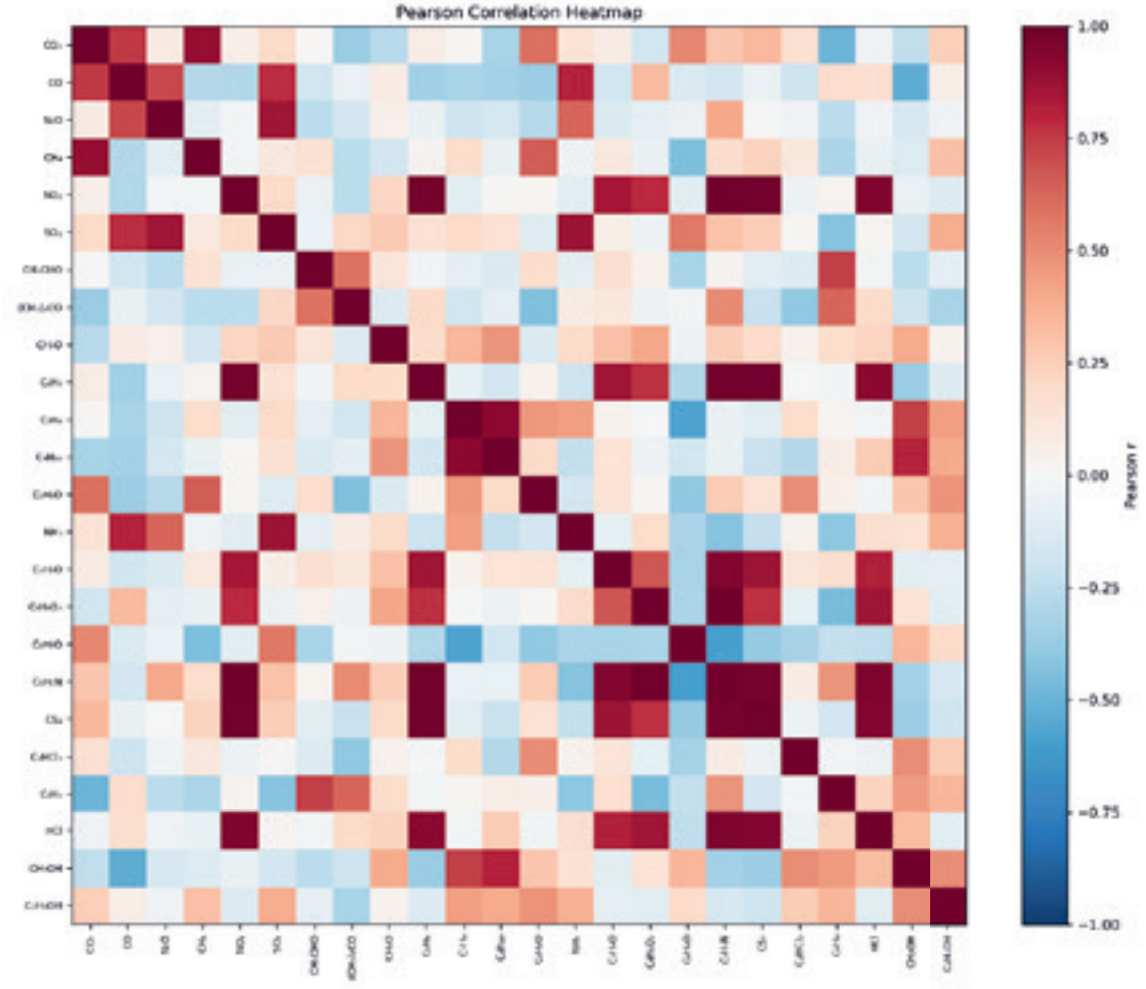

Figure 1. Correlation heatmap

Figure 1 presents the Pearson correlation heatmap illustrating linear relationships among the measured chemical species across sampling locations. Several statistically significant positive correlations were

identified, indicating that concentrations of certain compounds tended to increase or decrease concurrently. Warmer colours indicate stronger positive correlations, while cooler colours represent weak or negative relationships. The diagonal elements correspond to self-correlations (r = 1).

Notably, nitrogen dioxide (NO_2) exhibited strong positive correlations with carbon disulfide (CS_2), benzene (C_6H_6), and pyridine (C_5H_5N). These associations suggest the influence of shared emission processes or closely linked operational conditions rather than independent or random occurrence. In the context of hospital indoor environments, such co-variation may reflect combined contributions from laboratory activities, technical infrastructure, outdoor air infiltration, or ventilation system dynamics.

Additional clusters of moderate correlations were observed among aromatic and heterocyclic compounds, pointing toward source-related grouping or similar physicochemical behavior. Conversely, weak or negative correlations between certain pollutant pairs indicate divergent emission pathways, differences in chemical stability, or variable removal mechanisms such as air exchange, adsorption, or degradation. Collectively, these patterns underscore the heterogeneous and multi-pollutant nature of indoor air contamination in hospital workplaces.

Exploratory Factor Analysis (Principal Axis Factoring) was performed on standardized data after median imputation of <LOD values. The scree plot with the Kaiser threshold (Figure 2) indicates that RC1–RC6 have eigenvalues above 1 and are therefore retained according to the Kaiser criterion. RC1 explains approximately 26.2% of the variance, followed by RC2 (14.9%), RC3 (13.1%), RC4 (11.3%), RC5 (8.9%), and RC6 (4.6%).

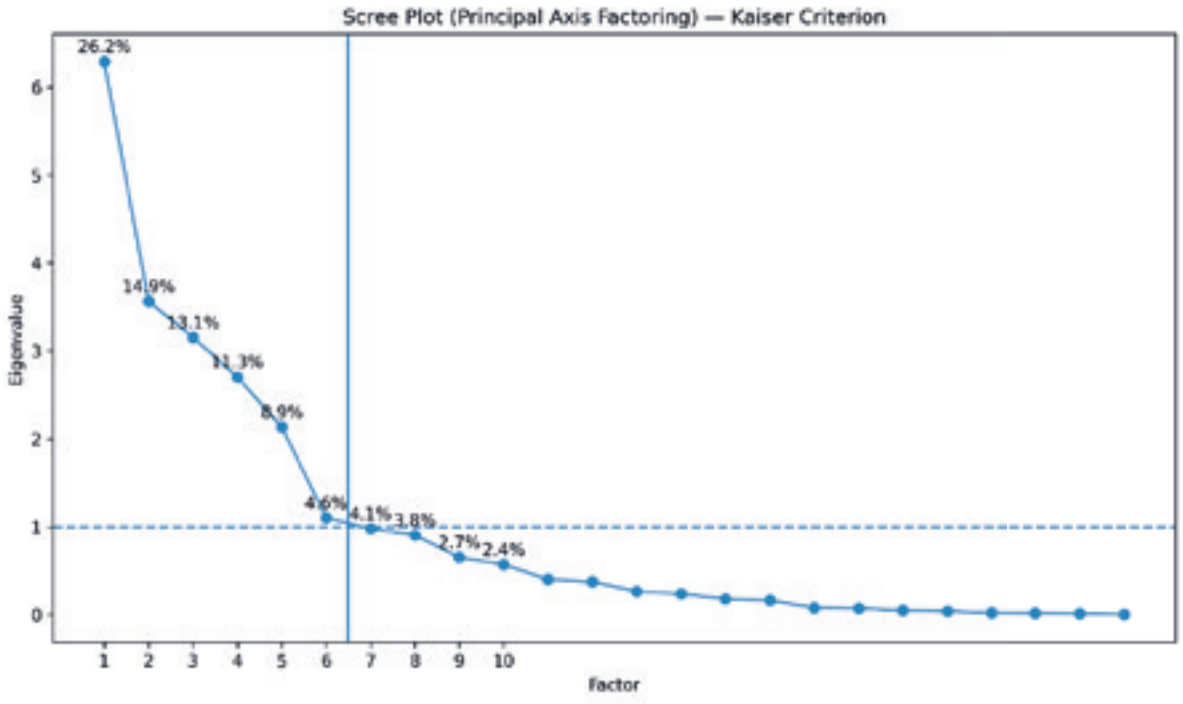

Figure 2. PCA scree plot

The cumulative explained variance shows that the first three components account for approximately 54.2% of the total variance, reaching approximately 65.4% by RC4 and approximately 79.0% by RC6. This variance distribution is consistent with real-world indoor air datasets characterized by multiple overlapping emission sources and interacting physicochemical processes rather than a single dominant factor.

The factor loading structure (Figure 3) demonstrates partial differentiation between emission patterns associated with occupancy and disinfectant use versus those linked to reactive gases and background influences. Operating rooms show greater alignment with ventilation- and disinfectant-related components, whereas other hospital areas exhibit broader dispersion, reflecting heterogeneous activities and variable ventilation regimes across the facility.

Table 2 presents the rotated factor loadings obtained from Exploratory Factor Analysis (Principal Axis Factoring) with oblique (Promax) rotation. Six rotated components (RC1–RC6) were retained based on eigenvalues greater than one according to the Kaiser criterion.

The corresponding eigenvalues were approximately 6.29 for RC1, 3.57 for RC2, 3.15 for RC3, 2.71 for RC4, 2.14 for RC5, and 1.11 for RC6, explaining 26.2%, 14.9%, 13.1%, 11.3%, 8.9%, and 4.6% of the total variance, respectively. Collectively, the six retained components accounted for approximately 79.0% of the overall variance, indicating a structured but heterogeneous multivariate system consistent with multiple partially overlapping emission sources.

Loadings with higher absolute values indicate stronger associations between individual chemical compounds and the corresponding component. Because an oblique (Promax) rotation was applied, correlations between components were permitted. Uniqueness values represent the proportion of variance in each compound not explained by the retained factors.

Formula	RC1	RC2	RC3	RC4	RC5	RC6	Uniqueness
NO_2	-0.993	0.031	0.006	0.017	-0.06	0.056	0.006
CS_2	-0.982	0.05	-0.016	0.007	-0.076	0.005	0.026
C_6H_6	-0.982	0.04	-0.024	0.044	-0.018	-0.003	0.032
C_5H_5N	-0.977	0.036	0.001	-0.007	0.095	0.063	0.032
HCl	-0.958	-0.043	0.029	-0.077	0.01	-0.047	0.071
C_8H_{10}	0.021	-0.948	-0.057	-0.149	0.02	0.001	0.074
C_7H_8	0.039	-0.944	-0.022	0.15	-0.002	-0.182	0.05
NH_3	0.024	-0.019	0.919	0.062	0.011	0.077	0.144
CO_2	-0.035	0.158	0.145	0.906	-0.161	0.013	0.105
CH_4	0.007	-0.021	-0.078	0.87	0.008	-0.087	0.23
CH_3CHO	0.006	0.096	-0.097	0.104	0.86	-0.148	0.209
CO	0.058	0.163	0.852	-0.2	-0.137	-0.2	0.146
C_3H_4O	-0.844	-0.046	-0.042	0.121	0.118	-0.222	0.207
SO2	-0.066	-0.036	0.842	0.117	0.034	0.12	0.256
CH_3OH	0.048	-0.808	-0.066	0.02	-0.189	0.305	0.211
C_8H_8	0.021	-0.025	-0.04	-0.21	0.792	0.085	0.318
$C_4H_8O_2$	-0.784	0.024	-0.012	-0.035	-0.052	-0.003	0.381
C_3H_8O	-0.028	-0.337	-0.195	0.739	0.094	0.071	0.287
$(CH_3)2CO$	0.004	0.124	0.004	-0.239	0.583	0.138	0.569
N_2O	0.042	0.139	0.567	-0.076	-0.246	-0.13	0.574
C_2H_5OH	0.094	-0.453	0.266	0.372	0.003	0.25	0.515
C_6H_6O	0.071	0.119	-0.041	-0.249	-0.26	0.418	0.675
C_2HCl_3	-0.038	-0.032	-0.041	0.356	-0.075	-0.049	0.861
CH_2O	-0.184	-0.342	0.131	-0.191	0.072	-0.221	0.742
Eigenvalue	6.293	3.565	3.156	2.704	2.135	1.103	
Variance (%)	26.2	14.9	13.1	11.3	8.9	4.6	
Total variance (Cum %)	26.2	41.1	54.2	65.5	74.4	79	

Note. Applied rotation method: Promax. Only loadings ≥ |0.001| displayed.

The first rotated component (RC1) is characterized by very strong loadings for reactive nitrogen- and sulfur-containing compounds and aromatic species, including NO_2, CS_2, benzene (C_6H_6), pyridine (C_5H_5N), hydrogen chloride (HCl), and acrolein (C_3H_4O). This pattern suggests a chemically reactive mixture potentially influenced by combined indoor–outdoor contributions, secondary reactions, and localized technical or laboratory-related activities. The dominance of oxidizing and sulfur-containing species indicates that RC1 reflects a reactive gas cluster rather than routine occupancy-driven emissions.

In contrast, the second component (RC2) is primarily associated with alcohol-based solvents and occupancy-related indicators, including isopropanol (C_3H_8O), ethanol (C_2H_5OH), acetone ($(CH_3)_2CO$), and carbon dioxide (CO_2). This component likely represents activity-driven emissions linked to cleaning, disinfection practices, and human presence, highlighting operational processes distinct from the reactive gas cluster captured by RC1.

The third and fourth components (RC3–RC4) capture additional structured variability within the dataset. Methane (CH_4) and sulfur dioxide (SO_2) exhibit relevant loadings within these factors, indicating background and combustion-related influences. These components likely reflect contributions from technical infrastructure, building energy systems, or ventilation supply air.

The fifth and sixth components (RC5–RC6) explain smaller proportions of total variance and may represent more localized or episodic emission processes rather than dominant system-wide sources. Their presence further supports the interpretation of indoor air quality in hospital environments as a multi-source and dynamically interacting system.

Table 3 presents the results of Welch's t-test comparing mean concentrations between operating rooms (OR) and other hospital areas, with Benjamini–Hochberg correction applied to control for multiple testing. Entries below the limit of detection (<LOD) were treated as missing values and excluded from group comparisons.

Statistically significant differences after correction were observed for carbon dioxide (CO_2), methane (CH_4), isopropanol (C_3H_8O), and acetone ($(CH_3)_2CO$).

CO_2, CH_4, and isopropanol concentrations were significantly higher in operating rooms, consistent with higher occupancy density and intensive use of alcohol-based disinfectants. In contrast, acetone concentrations were significantly lower in operating rooms compared with other hospital areas, suggesting differential emission patterns across functional zones.

A supplementary Mann–Whitney U test yielded comparable significance for the four dominant compounds but indicated additional marginal differences for several skewed variables. Nevertheless, Welch's test with BH correction was retained as the primary inferential framework due to unequal group sizes and variance heterogeneity.

For all remaining compounds, no statistically significant differences were detected after multiple-comparison adjustment.

Table 3. Comparison of mean concentrations between operating rooms (OR) and other hospital areas (Welch's t-test).

Formula	Mean (OR)	Mean (Other Areas)	T-Value	P-Value (BH)	Significant (P<0.05)
CO_2	639.233	170.998	13.895	1.37e-16	Yes
CH_4	2.795	1.057	10.713	6.69e-14	Yes
C_3H_8O	1.940	0.604	8.546	1.31e-05	Yes
CO	—	—	—	—	No*
C_6H_6O	—	—	—	—	No*
C_8H_8	—	—	—	—	No*

C_7H_8	1.670	1.318	1.342	2.79e-01	No
C_2HCL_3	0.088	0.044	2.107	1.54e-01	No
C_2H_5OH	4.403	2.358	1.897	1.90e-01	No
C_8H_{10}	0.068	0.967	−2.574	5.34e-02	No
$C_4H_8O_2$	0.053	0.690	−2.308	8.84e-02	No
HCL	0.273	0.573	−2.143	9.43e-02	No
CS_2	—	—	—	—	No*
$(CH_3)_2CO$	0.150	0.440	−3.876	2.18e-03	Yes
C_5H_5N	—	—	—	—	No*
C_2H_4O	—	—	—	—	No*
CH_2O	0.042	0.079	−1.579	2.63e-01	No
C_6H_6	0.250	0.631	−1.501	2.52e-01	No
N_2O	0.623	0.556	0.350	8.74e-01	No
NO_2	0.297	2.052	−1.049	4.18e-01	No
SO_2	0.210	0.206	0.058	9.91e-01	No
NH_3	0.162	0.151	0.117	9.91e-01	No
C_3H_4O	1.623	1.755	−0.475	8.19e-01	No
CH_3OH	0.330	0.332	−0.011	9.91e-01	No

"-" indicates insufficient valid measurements above the limit of detection (<LOD) within one or both groups to perform a reliable Welch's t-test.

For CO_2, CH_4, and isopropanol (C_3H_8O), mean concentrations were significantly higher in operating rooms compared with other hospital areas, consistent with higher occupancy density, controlled ventilation regimes, and the frequent use of alcohol-based disinfectants in these areas. Acetone ($(CH_3)_2CO$) exhibited significantly lower concentrations in operating rooms relative to other hospital areas, indicating potential differences in solvent-related emission patterns across functional hospital zones. For all remaining compounds, no statistically significant differences were detected after Benjamini–Hochberg correction. This suggests broadly comparable concentration levels across hospital areas for these substances and supports the interpretation of a heterogeneous but partially overlapping emission structure within the hospital environment.

DISCUSSION

The results of this study indicate that chemical exposure in hospital workplaces is governed by pronounced spatial heterogeneity and the coexistence of multiple gaseous pollutants, rather than by a single dominant emission source. Such heterogeneity is consistent with previous investigations of hospital indoor air quality, which have emphasized the combined influence of ventilation design, occupancy patterns, building characteristics, and cleaning and disinfection practices on airborne chemical composition (Saraga et al., 2011; de Carvalho et al., 2020). The present findings reinforce the view that hospital indoor air represents a dynamic system in which pollutant concentrations respond continuously to routine activities as well as to episodic events, rather than remaining at steady-state levels.

The most critical observation emerging from this study is the pervasive exceedance of acrolein (C_3H_4O), which exceeded the applied reference value at nearly all sampling locations. Acrolein is a highly reactive unsaturated aldehyde with well-established respiratory toxicity, capable of inducing airway inflammation, oxidative stress, and epithelial injury even at relatively low concentrations (Bein and Leikauf, 2011; Leikauf et al., 2011; Ghilarducci and Tjeerdema, 1995). Importantly, given that the present study employed FTIR-based real-time screening, the potential influence of spectral overlap with other oxygen-

ated volatile organic compounds (e.g., alcohols and carbonyl compounds) should be considered when interpreting the magnitude of measured concentrations. Although ethanol and isopropanol concentrations were generally below occupational limit values, their frequent use in hospital environments may still affect FTIR spectral fitting due to partial overlap in infrared absorption regions. While the multicomponent FTIR algorithm accounts for these compounds explicitly, the possibility of residual spectral interference, particularly for acrolein, cannot be fully excluded. Therefore, the reported acrolein exceedances should be interpreted with caution and considered indicative of a potential issue rather than definitive quantitative confirmation. While the widespread nature of the exceedances suggests that acrolein-related exposure may not be confined to isolated hotspots, confirmatory analytical measurements would strengthen the attribution of this signal exclusively to acrolein. Broader operational conditions, such as the use of specific chemical products, secondary formation reactions involving disinfectants, or ventilation regimes favoring accumulation during certain periods, likely contribute to the observed pattern. Similar concerns regarding aldehyde exposure in healthcare settings have been raised in occupational hygiene studies, particularly in environments characterized by intensive cleaning and disinfection activities (Logue et al., 2011; Nielsen et al., 2013; Ilić et al., 2020).

Nitrogen dioxide (NO_2) exceeded permissible levels at a subset of locations, indicating that reactive inorganic gases contribute to the overall exposure profile, although less consistently than acrolein. Although hospitals are not typically considered combustion-intensive environments, indoor NO_2 has been shown to originate from outdoor air infiltration, emergency power systems, medical or technical equipment, and inefficiencies in ventilation performance (Weschler, 2006; Brook et al., 2010; Morawska et al., 2013). The spatial variability observed in the present study suggests that local room characteristics and air-handling strategies play a decisive role in determining NO_2 concentrations, in line with previous observations in healthcare facilities (Daisey et al., 2003; Rouadi et al., 2010; Radović et al., 2022).

The detection of benzene (C_6H_6) exceedances at several locations is of particular relevance from an occupational-risk perspective, given its classification as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC, 2012). While benzene is most commonly associated with fuel combustion and industrial activities, its presence in hospital indoor air has been reported in relation to outdoor traffic infiltration, building materials, and certain laboratory or technical processes. Even though exceedances were observed at a limited number of locations, their occurrence underscores the importance of considering low-frequency but high-risk exposures within comprehensive workplace risk management frameworks.

Correlation analysis provided additional insight into potential relationships among measured pollutants. The strong positive associations observed between NO_2, carbon disulfide (CS_2), benzene, and pyridine indicate that these compounds tend to co-occur under similar environmental conditions. Although correlation does not imply causation, such co-variation patterns are commonly interpreted as evidence of shared emission processes or common controlling factors, such as ventilation performance or combined indoor–outdoor contributions. Comparable associations have been reported in previous indoor air studies, where reactive nitrogen oxides, aromatic hydrocarbons, and sulfur-containing compounds were linked through ventilation-driven mixing or overlapping source influences (de Carvalho et al., 2020).

The principal component analysis further supports the interpretation that hospital air quality is shaped by multiple partially independent processes. The retention of several components explaining a substantial proportion of the total variance indicates that no single factor dominates the chemical composition of indoor air. Instead, different components likely reflect background ventilation-related influences, activity-driven emissions associated with cleaning and solvent use, and more localized or episodic contributions from technical or laboratory operations. Importantly, the identification of a component strongly influenced

by acrolein suggests that this compound follows a distinct variation pattern embedded within a broader mixture of reactive gases, rather than behaving as an isolated pollutant.

Differences observed between operating rooms and other hospital areas provide additional context for interpreting the exposure patterns. Higher concentrations of carbon dioxide, methane, and isopropanol in operating rooms are consistent with elevated occupancy, controlled ventilation regimes, and intensive use of alcohol-based products during clinical procedures (Seppänen and Fisk, 2004). The importance of optimized ventilation performance in critical care environments, including operating rooms and intensive care units, has been emphasized in previous studies addressing airflow control, contaminant dilution, and pressure differentials in healthcare settings (Saran et al., 2020). This finding aligns with previous studies demonstrating that operating rooms generally maintain stricter air quality control than general wards or technical areas (Memarzadeh and Manning, 2002).

Overall, the present findings highlight that chemical exposure in hospital workplaces is driven by a combination of background conditions and activity-specific processes, resulting in complex and temporally variable exposure patterns. From an occupational-health perspective, this complexity underscores the limitations of assessment strategies based solely on average concentrations or a narrow set of indicators, and it emphasizes the value of real-time, multicomponent monitoring approaches for identifying priority pollutants and guiding targeted risk management measures.

CONCLUSION

This study provides original real-time evidence on airborne chemical exposure in hospital workplaces during the summer period, demonstrating that indoor air quality is characterized by pronounced spatial heterogeneity and activity-driven concentration fluctuations rather than uniform background conditions. The results confirm that chemical exposure in healthcare facilities is governed by multiple concurrent factors, including ventilation performance, chemical product usage, occupancy density, and operational practices, which together shape complex and temporally variable exposure patterns.

A key outcome of this investigation is the identification of acrolein as a critical pollutant of occupational-health relevance. The near-ubiquitous exceedance of reference values for acrolein suggests that aldehyde-related exposure may represent a relevant occupational-health concern under the investigated summer operating conditions. However, given the screening-based analytical approach, further confirmatory measurements are warranted before definitive regulatory conclusions are drawn.

Differences observed between operating rooms and other hospital areas further emphasize that chemical exposure cannot be adequately addressed through generalized indoor air quality assumptions. Area-specific exposure profiles, shaped by distinct activities and ventilation characteristics, require differentiated assessment and control strategies. The results therefore support a shift from uniform monitoring approaches toward more context-sensitive occupational hygiene practices within healthcare facilities.

Although the present study is based on real-time screening measurements, it provides a robust framework for identifying priority substances and exposure scenarios that warrant further investigation. The observed frequency and magnitude of exceedances for selected pollutants, particularly acrolein, suggest that existing ventilation and chemical management practices may require reassessment under certain seasonal operating conditions. These findings highlight the importance of integrating continuous or high-temporal-resolution air quality monitoring into occupational health programs to support evidence-based decision-making and protect healthcare workers' health.

Conflict of Interest
The authors declare no conflict of interest.

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Recived: November 31, 2025

Accepted: January 16, 2026