

Article

Not peer-reviewed version

Assessment of Formaldehyde's Impact on Indoor Environments and Human Health via the Integration of Satellite Tropospheric Total Columns and Outdoor Ground Sensors

[Elena Barrese](#) , [Marco Valentini](#) , [Marialuisa Scarpelli](#) , [Pasquale Samele](#) , [Luana Malacaria](#) , [Francesco D'Amico](#) ^{*} , [Teresa Lo Feudo](#) ^{*}

Posted Date: 31 October 2024

doi: 10.20944/preprints202410.2512.v1

Keywords: Lamezia Terme; formaldehyde; SP5; indoor air quality; outdoor air quality



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a Creative Commons CC BY 4.0 license, which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Article

Assessment of Formaldehyde's Impact on Indoor Environments and Human Health via the Integration of Satellite Tropospheric Total Columns and Outdoor Ground Sensors

Elena Barrese ¹, Marco Valentini ¹, Marialuisa Scarpelli ¹, Pasquale Samele ¹, Luana Malacaria ², Francesco D'Amico ^{2,3,*} and Teresa Lo Feudo ^{2,*}

¹ Department of Medicine, Epidemiology, Occupational and Environmental Hygiene - National Institute for Insurance against Accidents at Work, Area Industriale Comp. 15, I-88046 Lamezia Terme, Catanzaro, Italy; e.barrese@inail.it (E.B.); ma.valentini@inail.it (M.V.); m.scarpelli@inail.it (M.S.); p.samele@inail.it (P.S.)

² Institute of Atmospheric Sciences and Climate - National Research Council of Italy, Area Industriale Comp. 15, I-88046 Lamezia Terme, Catanzaro, Italy; l.malacaria@isac.cnr.it (L.M.)

³ Department of Biology, Ecology and Earth Sciences - University of Calabria, Via Bucci Cubo 15B, I-87036 Rende, Cosenza, Italy; f.damico@isac.cnr.it (F.D.)

* Correspondence: f.damico@isac.cnr.it (F.D.); t.lofeudo@isac.cnr.it, (T.L.F)

Abstract: Formaldehyde (HCHO) is harmful to human health and an adequate assessment of its concentrations, both in outdoor and indoor environments, is necessary in the effort of risk mitigation. In this research, ground indoor and outdoor HCHO measurements have been integrated with the analysis of tropospheric total columns obtained by satellite surveys to assess the concentrations of HCHO in a number of environments, exploiting the proximity of a World Meteorological Organization – Global Atmosphere Watch (WMO/GAW) observation site in Calabria, Southern Italy to a National Institute for Insurance against Accidents at Work (INAIL) department in the municipality of Lamezia Terme. Meteorological parameters gathered at the WMO station have also been used to provide additional data and test new correlations. Using statistical significance tests, the study demonstrates the presence of a correlation between indoor and outdoor HCHO concentrations, thus showing that an exchange between indoor and outdoor formaldehyde does occur. Rooms located in the building where indoor measurements took place have also demonstrated degrees of susceptibility to HCHO exposure which are correlated with the orientation of prevailing wind corridors in the area. The new findings constitute an unprecedented characterization of HCHO hazards in Calabria and provide regulators with new tools on how to mitigate formaldehyde-related risks.

Keywords: Lamezia Terme; formaldehyde; SP5; indoor air quality; outdoor air quality

1. Introduction

Formaldehyde (HCHO or CH₂O) (FA), one of the most common volatile organic compounds (VOC), is a colorless, irritating and extremely volatile gas [1]. It has been known for decades to be a major pollutant in the context of indoor air quality [2–12]. In 2004, formaldehyde was included in Group 1 by the International Agency for Research on Cancer (IARC) [13] defining it based on scientific evidence, as a certain carcinogen for humans. Subsequent investigations (monograph 100F of 2012) confirm this classification based on epidemiological evidence sufficient to determine that FA causes leukemia and death of the nasopharynx [14,15]. The European Commission classified formaldehyde as carcinogen (Category 1B), mutagen (Category 2), and toxic for the acute toxicity category 3 in June 2014 [16].

Over the years, exposure to this molecule has been linked to indoor air pollution, with the WHO raising concerns about its negative health effects [17]. Millions of people in modern society spend about 90% of their time indoors [18–20]. In Italy, research has also focused on monitoring indoor air quality especially in buildings of critical importance, such as hospitals and schools [21].

Many health hazards are linked to poor indoor air quality (IAQ), a parameter that can be affected by various factors such as wood-based building materials, paper products, personal care products, tobacco smoke, and inadequate HVAC (heating, ventilation, and air conditioning) systems [22–30].

There are also several outdoor sources of FA. Among anthropogenic sources are vehicle emissions, biofuel and coal combustion, industrial processing, and wood product building materials; this compound is also released due to secondary formation from other reactive volatile organic compounds [31–36]. Wildfires also contribute to significant FA emissions in the atmosphere, and the consequent diffusion of air masses and plumes can significantly expand the areas affected by direct FA exposure [37–45]. In addition to anthropogenic pollution, the location (e.g., whether an area is rural or urban), temperature, relative humidity, wind regime, cloud cover, season, and time of day can all influence the concentration of formaldehyde in ambient air [46–51]. FA has also been confirmed to be present in outer space, ranging from interplanetary to interstellar environments [52–55].

With respect to absolute concentrations, those of indoor FA are higher than their outdoor counterparts [56–66]: in the conventional indoor environment average concentrations are typically about 20–40 $\mu\text{g}/\text{m}^3$, while outdoor concentrations hover around 1–4 $\mu\text{g}/\text{m}^3$; lower concentrations are reported in rural areas, while higher levels are observed in polluted cities [67].

The WHO [68] have established an indoor air quality guideline for formaldehyde, but there is no similar guideline for outdoor air, even though it is considered a toxic air contaminant. This lack of an outdoor guideline makes it difficult to assess the potential indoor contributions from outdoor formaldehyde. Recent studies have examined the relationship between indoor and outdoor air to investigate how outdoor formaldehyde affects indoor concentrations; results from leading literature show that outdoor formaldehyde can make a significant contribution to indoor levels [69].

Due to the limited availability and spatial variability of ground-based measurements, some studies have used satellite data to map outdoor surface formaldehyde concentrations [69–71].

This research study aims to investigate the long-term outdoor contribution of formaldehyde to indoor concentrations by correlating satellite data with outdoor and indoor measurements. Total column data are frequently used in research to gather data that would not otherwise be obtainable by surface measurements alone [72]. In this research, HCHO column data from Sentinel-5P VCD have been used to map surface air HCHO concentrations and connect them to ground data in the Mediterranean region, where this field of research is new. Because the formaldehyde concentration in indoor air is usually inversely correlated with the air exchange rate, measurements of microclimatic parameters and air exchange were carried out.

This study, based on a 2021 measurement campaign performed in Lamezia Terme (Calabria, Southern Italy), is divided as follows: Section 2 describes the sites where the campaign took place, their peculiarities, and the instruments used for measurement; Section 3 describes the materials and methods used for this assessment; Section 4 and 5 show the result of the evaluation and their discussion, respectively; Section 6 concludes the paper.

2. Experimental Campaign Sites, Instruments, and Sampling Times

2.1. Experimental Campaign Sites

An experimental campaign was performed in 2021 at the coastal infrastructure of INAIL (National Institute for Insurance against Accidents at Work) and the WMO/GAW (World Meteorological Organization – Global Atmosphere Watch) regional station of Lamezia Terme (code: LMT), operated by the National Research Council of Italy – Institute of Atmospheric Sciences and Climate (CNR-ISAC), located nearby. The GAW experimental site (Lat: 38.88 N; Lon: 16.24 E) is located 600 meters from the Tyrrhenian coastline of Calabria, at an elevation of 6 meters above sea level. The Catanzaro isthmus between the Tyrrhenian and Ionian seas is the narrowest point in the

entire Italian peninsula, with a distance of approximately 31 kilometers between the two coastlines (Figure 1); the isthmus separates the Serre Massif, located in the South, from the coastal chain (*Catena Costiera*) in the northwest and the Sila Massif in the North. The particular orographic configuration of the isthmus results in a well-defined W/NE wind circulation, which is characterized moderate wind breezes from the sea (NW–SW), mainly developed during daytime, while northeastern gentle wind breezes from land mainly affect the night-time period [73,74]. Over the course of LMT's observation history, local wind circulation was further characterized using LiDAR and other techniques [75–77]. The 10/28 (100/280 °N) runway orientation of the Lamezia Terme International Airport (IATA: SUF; ICAO: LICA) located 3 kilometers north from the INAIL and ISAC research centers also shows that local air traffic is subject to the same wind regimes affecting atmospheric measurements at the GAW site.

The LMT station, located within Lamezia Terme's industrial area, is influenced by various sources of anthropogenic emissions: early research on greenhouse and reactive gases observed at ISAC ever since 2015 indicated the airport, the A2 highway, livestock farming and agriculture as emission sources in the area [78]. Research on case studies also showed relevant inputs from Saharan dust events [79] and summer open fire emissions [80]. A study on seven years of methane data showed that northeastern-continental winds were enriched in CH₄, while western-seaside winds yielded lower values; in addition to that, low speed winds from the northeast were linked to the highest observed mole fractions, and vice versa, high speed winds from the same air corridor were linked to low concentrations [81]. A consequent study on surface ozone (O₃) however showed a reversed pattern, thus demonstrating that each atmospheric compound can have peculiar impacts on local observations [82].



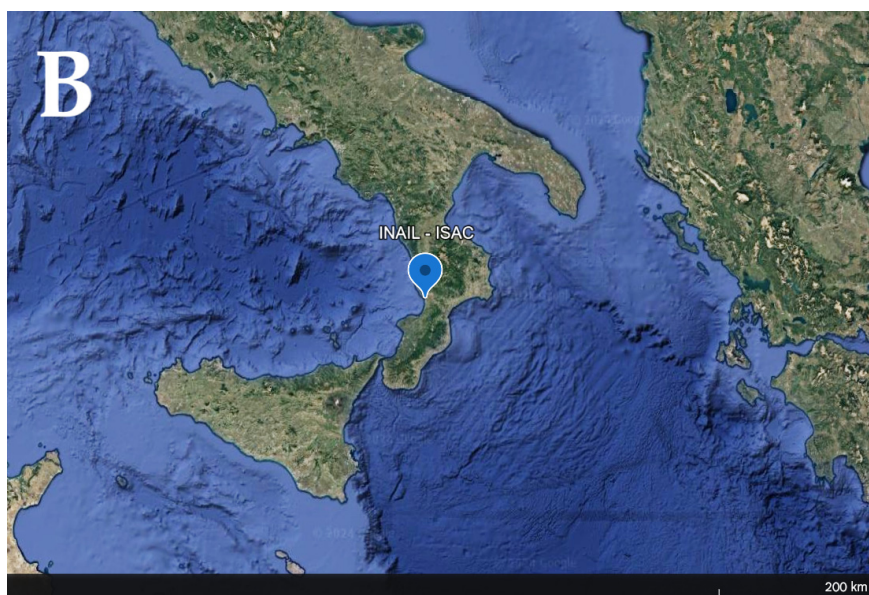


Figure 1. A: Details on the location of both research centers in the industrial area of Lamezia Terme.
B: Location of the two research centers in southern Italy.

Research on LMT data also relied on new methods to differentiate between natural and anthropogenic emissions by highlighting weekly cycles. In fact, while natural emissions are affected by daily to yearly cycles, anthropogenic emissions show weekly variations attributable to different anthropic activities throughout the week. Following cross-station studies on aerosols and their anthropogenic emission sources [83,84], another study evaluated with unprecedented detail weekly patterns at LMT and also proposed a new methodology for similar assessments on a global scale [85]. Additional and new insights on local emission sources were possible thanks to an environmental evaluation of the first 2020 COVID-19 lockdown period in Italy: with anthropic activities reduced to a minimum under those exceptional circumstances, several emission sources in the area could be pinpointed [86]. New research has focused on tropospheric or PBL (Planetary Boundary Layer) influence on the surface concentrations of key pollutants under different wind regimes [87].

2.2. Total tropospheric Vertical Column (TVC) of HCHO by Satellite

Satellite outdoor measurements of the total vertical column (TVC) of formaldehyde (HCHO) in the troposphere have been carried out using Sentinel-5P satellite products, a global air pollution monitoring satellite launched by ESA on October 13th, 2017 as part of the Copernicus mission [88]. Sentinel-5P uses a high inclination orbit (about 98.7°), defined as the angular distance of an orbital plane from the equator. Sentinel-5P's has a sun-synchronous, near-polar orbit. Said orbit leads 5P to cross the equator at 13:30MLST (Mean Local Solar Time); this implies that the surface of the Earth is always illuminated, at the same angles, by the Sun. 5P has a total orbital cycle of 16 days (14 orbits per day, or 227 orbits per cycle) and the orbital reference altitude is approximately 824 km. The advanced Tropospheric Monitoring Instrument (TROPOMI) for detailed atmospheric measurements carried onboard Sentinel-5P is located in a low Earth orbit in the afternoon polar region with a swath width of 2600 km. There are four spectrometers, each electronically split in two bands (two channels in SWIR, two channels in VIS, two channels in UV, and two channels in NIR), with a radiometric accuracy in absolute terms of 1.6% (SWIR) to 1.9% (UV) compared to Earth's spectral reflectance. With the finest spatial resolution of 3.5x5.5 km² and a high signal-to-noise ratio among the most advanced atmospheric monitoring spectrometers currently available, it has been performing global scans since August 6th, 2019. Operational Level 2 (L2) products are currently available to the public and several research works in literature cover the results [89–91]

2.3. Indoor and Outdoor Sampling Sites, Instruments and Times

Regarding indoor monitoring, a total of twelve office rooms, one room used with photocopiers, and one was a large training room (often used to host external events), were investigated from March to June 2021. The samplings were carried out during normal working activities, reproducing a real indoor workplace environment representative of standard employee risk to FA exposure. A typical time point (09:00-13:00 AM) was identified to characterize the diurnal working trend. The samplers were placed on the desk close to the worker, one meter away from the walls of each room. In smaller offices, one sampling point was considered, however in larger rooms two points were subject to these measurements. Three samples were taken in each sampling point over three consecutive days. The furniture provided for each workstation was a desk, a bookcase, and a chest of drawers. All offices have windows and a centralized air recycling system.

In conjunction with indoor formaldehyde measurements, samplers were placed outside the structure on a terrace adjacent to the monitored offices at a height of 1.5 meters. In addition to HCHO monitoring, comprehensive microclimatic measurements were taken at both indoor and outdoor locations with a sampling rate of one minute. Furthermore, the indoor air exchange rate from the recycling system was assessed.

Indoor microclimatic measurements were performed using two integrated data loggers (LSI-LASTEM model M-Log - ELO009) each equipped with a psychrometric sensor mod: an ESU102A, which acquired Wet and Dry forced ventilation temperatures according to the ISO7726 standard; and a hot wire anemometer mod: an ESV308 for measuring mean air speed and turbulence intensity with a high rate. The measurement precision of employed psychrometers is ± 0.1 °C for temperature and $\pm 2\%$ for RH (relative humidity) in the temperature range of 5-45 °C, while the anemometer has an accuracy ± 0.06 m/s in the 0.1-4 m/s range, and ± 0.08 m/s in the range of 0.4-3.0 m/s.

The instruments were positioned on a tripod at heights of approximately 1.5 meters, and close to the sampling system indoor measurement points. The acquisition rate was one second for each parameter, and after 60 seconds of continuous measurement, the averages were stored in the aboard memory. Besides microclimatic conditions, a balometer TSI Accubalance 8380 was used to measure the air flux from ceiling-mounted cassette air conditioner when operating.

Outdoor meteorological measurements were collected by the station located in the same area in which the chemical measurements were acquired. Since 2015, several instruments have been in operation at the WMO/GAW LMT as part of a number of different monitoring programs. In this study, we used an automatic weather station (Vaisala WXT520, Finland) collecting data at a height of 10 meters above ground level. This station, which is part of the WMO/GAW instrument pool, records meteorological parameters such as wind velocity (m/s) and direction (°), temperature (°C), relative humidity (%), barometric pressure (hPa), and accumulated rainfall (10-minute averages). The wind sensor consists of an array of three ultrasonic transducers that are equally spaced in a horizontal plane: the time required for ultrasounds to travel from each transducer to the other two was used by the instrument to determine wind speed and direction. The precipitation sensor was used to detect the impact of individual rain drops and the generated signals were proportional to drop volume; this allowed the signal from each drop to be converted directly to accumulated rainfall. An advanced RC oscillator and two reference capacitors were used to continuously measure the capacitance of the pressure, temperature, and humidity sensors. The temperature dependence of the pressure and humidity sensors is compensated by the transmitter's microprocessor, thus allowing the instrument to detect ambient air pressure, RH, and temperature with a sampling rate of one minute between measurements.

3. Material and Methods

3.1. Outdoor Tropospheric TVC Formaldehyde Satellite Methods for Data Processing

In accordance with technical documents and recommendations, offline TROPOMI L2 HCHO data gathered between March 1st and August 31st, 2021 have been used in this research. HCHO data were provided in either in mol/m² or in molecule/cm² using a multiplication factor of 6.02214×10^{19} ,

as suggested by ESA [92]. An algorithm programmed in MATLAB-R2016a, comprised of several consecutive digital processing steps, was used to reprocess data stream and HCHO column data.

The algorithm operates as follows: daily TROPOMI data are downloaded in netcdf format; said data are parsed through and all required variables are processed; coordinates (latitude, longitude) and time are extracted and converted according to the satellite's track and scanning time; gas data is extracted from the global matrix and consequently stored in an array focused on a particular region of interest; the array is therefore georeferenced and all values with a Q_a value less than 0.5 are excluded. This step is in accordance with the recommendations on TROPOMI data processing, as the quality of data is normally assigned a value ranging from 0 to 1 for all registered columns, and only columns with a Q_a greater than 0.5 are recommended (cloud radiance fraction at 340 nm < 0.5, no error flag, surface albedo ≤ 0.2 , no snow/ice warning, Solar Zenith Angle (SZA) $\leq 70^\circ$, and air mass factor > 0.1) [93,94].

The algorithm includes a function aimed at performing a direct comparison between a target site located at precise coordinates, and satellite measurements in its vicinity. The method ultimately relates the minimum distance to the target site to the smallest distance datum in the array for processing.

3.2. Formaldehyde Indoor/Outdoor Surface Analysis Methods

Indoor and outdoor formaldehyde was sampled using personal sampling pumps equipped with adsorbent tubes containing a front bed of 300 mg DNPH-coated silica gel and a back bed of 150 mg DNPH-coated silica gel (NIOSH 2016). The tubes were eluted with 5 mL of HPLC-grade acetonitrile (ACN) and analyzed using an HPLC Shimadzu (model LC-20 AB) coupled with a binary pump and UV-VIS detection (SPD-20 A/AV) at a wavelength of 365 nm. A calibration curve with an R^2 value of 0.9994 was established to quantify formaldehyde concentrations. The detection limit for formaldehyde was 0.02 $\mu\text{g/mL}$, and the recovery rate was 90-105%.

3.3. Statistical Methods

A statistical analysis was performed on the chemical and physical parameters and some correlation tests were performed. With regard to the meteorological and microclimatic parameters (outdoor and indoor), the first step was to organize homogeneous datasets starting from raw data and then aggregating them on an hourly basis for all the parameters considered: outdoor Temperature, T_{out} °C, indoor Temperature, T_{ind} °C, outdoor Relative Humidity, $RH_{\text{out}}\%$, indoor Relative Humidity, $RH_{\text{in}}\%$, outdoor Wind Speed and Direction, WS_{out} and WD_{out} , indoor Wind Speed, WS_{in} , and direction, WD_{in} . A homogeneous dataset is organized starting from raw data gathered every one minute, following the aggregation on hourly basis of all considered meteorological parameters. Statistical methods for quality control and validation are applied to the raw data to remove outliers and problems that may be due to technical issues.

In order to perform comparisons between concentrations of formaldehyde accumulated between 11:00 and 15:00 UTC, the mean and standard deviation (SD) were calculated starting from the hourly mean homogenized dataset in the interval between 11:00 and 15:00 UTC. Spearman's rank correlation coefficient (SR) [95,96] was then applied to these new datasets. The SR is a method used to test the strength and direction (positive or negative) of the correlation, related or associated, between two variables, and is defined as Pearson's correlation coefficient between ranked variables [97]. For a sample of size n , the variables x and y are converted into the ranks R_x and R_y , respectively, and the SR coefficient, ρ , is calculated as follows:

$$\rho = (\text{cov}(R_x, R_y)) / (\sigma R_x \sigma R_y) \quad (1)$$

where cov is the covariance of the rank variables, σR_x and σR_y are the standard deviations of the rank variables. The Spearman Rank Correlation can have a value ranging from +1 to -1 and its interpretation is similar to that of the PCC (Pearson Correlation Coefficient).

4. Results

4.1. Outdoor Formaldehyde

The possibility of studying atmospheric concentrations at LMT, in the absence of previous and continuous measures of formaldehyde, is provided by the use of satellite data. On the basis of this information, we performed an analysis of outdoor HCHO tropospheric column provided by the SP5 mission, using the methodology described in section 3.2, between March 1st and August 31st, 2021.

Seasonal variations in environmental parameters and FA concentrations are shown in Figure 2. The daily mean values of VCD HCHO were used to compute monthly and seasonal averages, along with median values and percentile thresholds (5th, 25th, 75th, and 95th percentiles). A seasonal trend emerged, with higher monthly mean formaldehyde concentrations observed during warm summer months. The highest monthly average VCD HCHO value, $1.3 \times 10^{16} \pm 0.6 \times 10^{16}$ molecules/cm² (blue spots), was recorded in July 2021, whereas lower concentrations were detected in March and April.

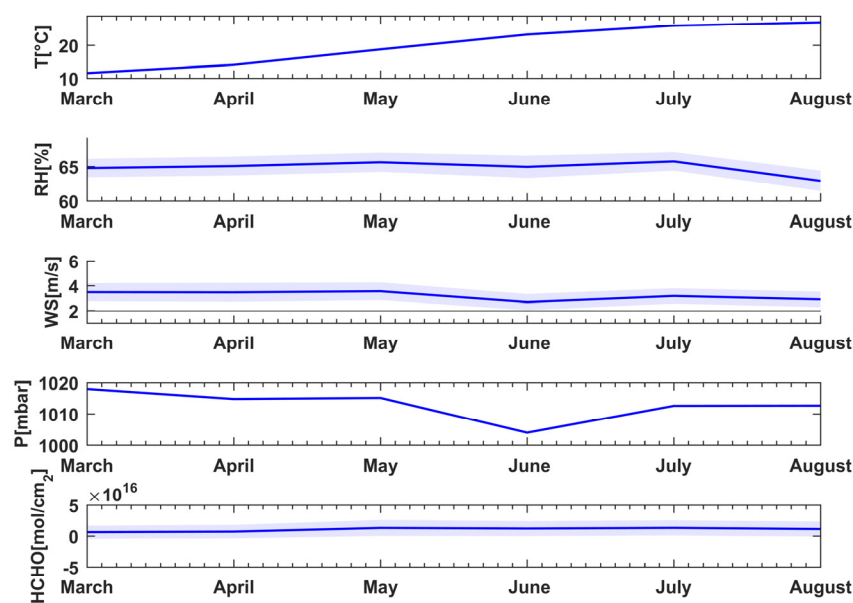


Figure 2. Monthly environmental and HCHO values observed at the site during the 2021 campaign. From top to bottom, temperature (°C), relative humidity (%), wind speed (m/s), pressure (mbar), and VCD HCHO count (molecules/cm²). Shaded areas, where present, show error bars.

In Figure 3, surface and columnar data measured at the satellite’s passage in correspondence of the experimental site are highlighted, and a single data per day can be compared directly with in situ data. The comparison between surface measurements and satellite dataset showed that in correspondence of the recorded outdoor HCHO concentration peaks, an increase is observed in both cases with a similar trend.

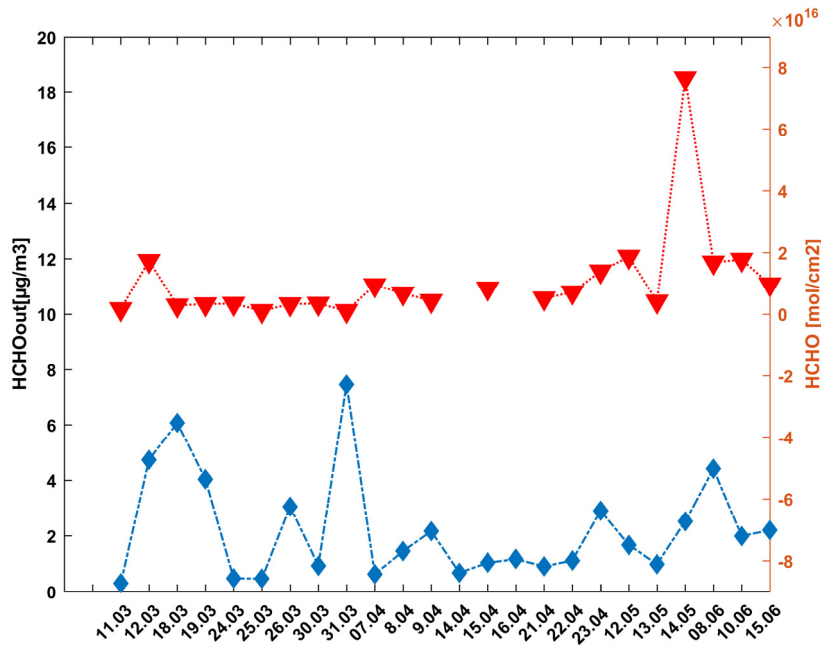


Figure 3. Comparison between near-surface outdoor HCHO cumulated concentrations values in $\mu\text{g}/\text{m}^3$ (blue line) at LMT and tropospheric column in molecules/ cm^2 (red points) by TROPOMI L2 at 13:00 local time.

This data evaluation emphasizes the importance of combining satellite observations with ground-level measurements to obtain a comprehensive understanding of formaldehyde distribution and its influencing factors, particularly in complex environments like the Mediterranean region; research previously carried out at LMT on multi-year datasets of continuous measurements evidenced opposite surface concentration patterns for methane [81] and ozone [82], thus showing that these concentrations need enhanced analyses to be adequately assessed.

In Figure 4, we reported the indoor and outdoor average concentrations of formaldehyde detected in each room within the INAIL research center in Lamezia Terme. In general, indoor concentration values of FA are higher compared to their outdoor counterparts, as confirmed by the outdoor/indoor ratio that is always less than one, with the exception of rooms 10, 12, 13, 14.

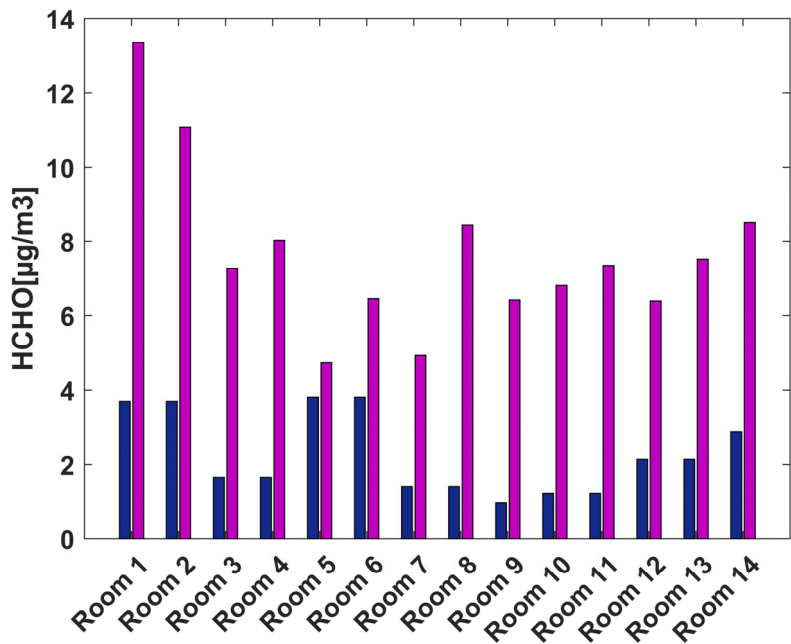


Figure 4. Comparison of outdoor and indoor HCHO concentrations in all rooms subject to the 2021 campaign. Purple bars indicate indoor concentrations, while blue bars indicate outdoor values.

In order to investigate possible correlations between meteorological/microclimatic variables, and formaldehyde concentrations during the sampling campaign, we calculated Spearman and significance tests following the descriptions reported in section 3.3. The results are shown in Table 1.

Table 1. Spearman regression matrix between outdoor microclimatic parameters and HCHO external concentrations.

	HCHO _{out}	VCD HCHO	T _{out.}	RH _{out.}	WS _{out}
HCHO _{out}	–				
VCD HCHO	0.169	–			
T _{out}	0.168	0.550***	–		
RH _{out.}	0.392**	0.164	0.293*	–	
WS _{out}	-0.130	0.106	-0.301*	0.202	–

* p < 0.05, ** p < 0.01, *** p < 0.001.

The reported data represent the ρ Spearman values, while footnotes (*) indicate the statistical significance level of each test. Formaldehyde outdoor concentration is well correlated with, a p-value of 0.006, with relative humidity whereas the total column of HCHO is highly correlated with external temperature, yielding a p-value of < 0.001.

Table 2. Spearman’s regression matrix between all the indoor and outdoor measurements.

	T _{in}	RH _{in}	WS _{in}	T _{out.}	RH _{out}	WS _{out}	HCHO _{in}	HCHO _{out}
T _{in}	–							
RH _{in}	0.019	–						
WS _{in}	0.029	-0.082	–					
T _{out}	0.405 **	0.654 ***	0.030	–				
RH _{out}	-0.051	0.642 ***	-0.141	0.293 *	–			
WS _{out}	-0.103	0.082	-0.098	-0.301 *	0.202	–		
HCHO _{in}	-0.057	0.276	-0.298 *	0.000	0.254	0.244	–	
HCHO _{out}	-0.086	0.293	-0.130	0.168	0.392 **	-0.130	0.377 **	–

* p < 0.05, ** p < 0.01, *** p < 0.001.

The reported Spearman’s test values indicate that outdoor FA concentrations are well correlated (p-value = 0.008) with their indoor counterparts, as is the indoor RH with outdoor temperature and relative humidity p-value, respectively (< 0.001). Furthermore, the analysis shows a weak but likely negative correlation between indoor FA concentration and indoor speed.

4.2. Integration of meteorological parameters

Accounting for the addition of Vaisala WXT520 meteorological data, a cross-evaluation was performed for 24 days, from March 11th to June 15th, 2021. From the analysis of surface meteorological data shown in Figure 5, we note four different types of wind regimes, which have also observed in recent peplospheric assessments at the same site [87]: well-developed sea-land breeze cycle with wind direction shifting between west and east during daytime (sea-breeze with onshore flow) and nighttime (land breeze with offshore flow) respectively; (green box) not complete (NC) sea-land breeze, i.e., where wind direction during night comes from south, black box; synoptic wind flow, from the west (synoptic wind); wind direction coming from East (during night). From the data shown in Figure 5, we observed a daily cycle in the time series of physical parameters. During the night and early morning, the surface layer is stable whilst, during the central hours of the day, the surface layer is neutral or unstable, depending on weather conditions.

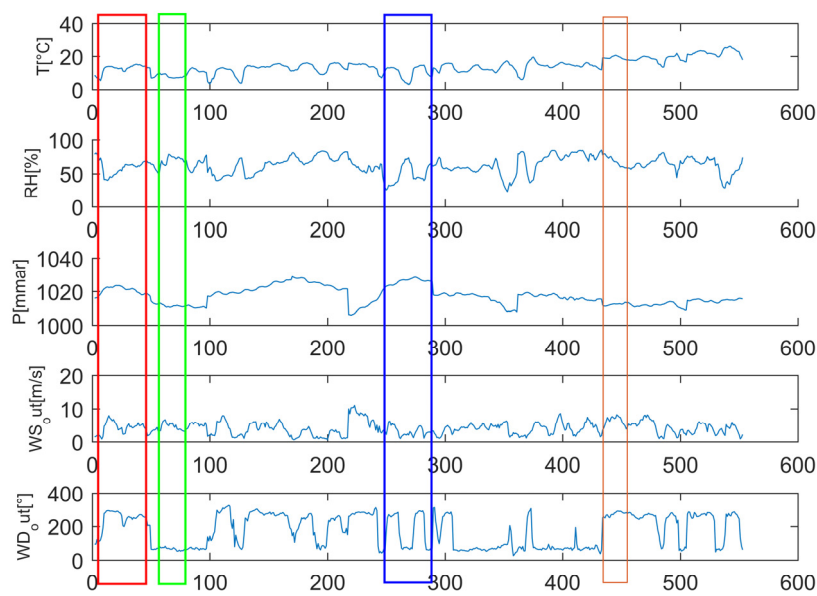


Figure 5. Wind regimes for every day of the campaign, which are attributed as follows: breeze (green box); not complete (NC) breeze (black box); western synoptic flow (orange box); eastern synoptic flow (blue box). Additional evaluations on the effects of these regimes on local observations are available in D’Amico et al. (2024e) [87].

Looking at the acquired data and examining each day of the campaign, a bivariate statistical analysis shows how local winds affect the in situ outdoor FA. A bivariate statistical analysis is used to provide useful evidences aimed at investigating how local winds affect outdoor FA observed by in situ measurements. To this end, daily HCHO values are analyzed as a function of wind speed and direction observed at LMT station during the experimental campaign (Figure 6). The highest HCHO concentrations ($> 5\mu\text{g}/\text{m}^3$) occur with winds blowing from east-northeast (E-NE) (Figure 6), a pattern in accordance with methane peaks at the same site described in D’Amico et al. (2024a) [81].

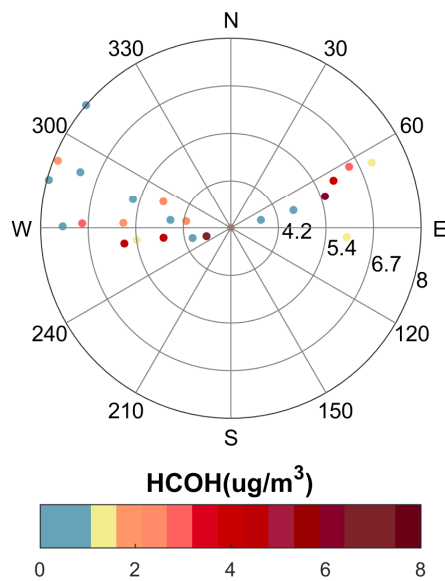


Figure 6. Results of bivariate analyses on accumulated daily values of HCHO surface outdoor concentration as a function of wind speed and direction during the day of the monitoring campaign.

The findings shown in Figure 6 suggest that inland air masses play a key role in promoting the occurrence of elevated levels of these atmospheric tracers under local circulation conditions (mountain breeze, wind speed <5 m/s). A cyclonic event characterized by higher wind speed is associated with lower values observed for this air mass provenance. In general, two different situations occur when considering the west and southwest (W-SW) sectors: the first is linked to the establishment of the breeze regime, with winds below 6 m/s, characterized by the transport of sea spray, which occurred most frequently at LMT, especially in spring and summer; the second is related to the synoptic conditions with wind speeds above 8 m/s, which are characterized by the transport of different types of gases and aerosols into the atmospheric column. With this wind regime, several transport events of aerosols from the Sahara [79], volcanic ash from Etna and Stromboli located nearby at 2 km, 3357 m above sea level, and 1 km, 924 m above sea level, from the site offshore [80], respectively, are observed. In addition, CO and CO₂ are transported especially in summer due to the frequent fires that occur in the Calabrian region [80].

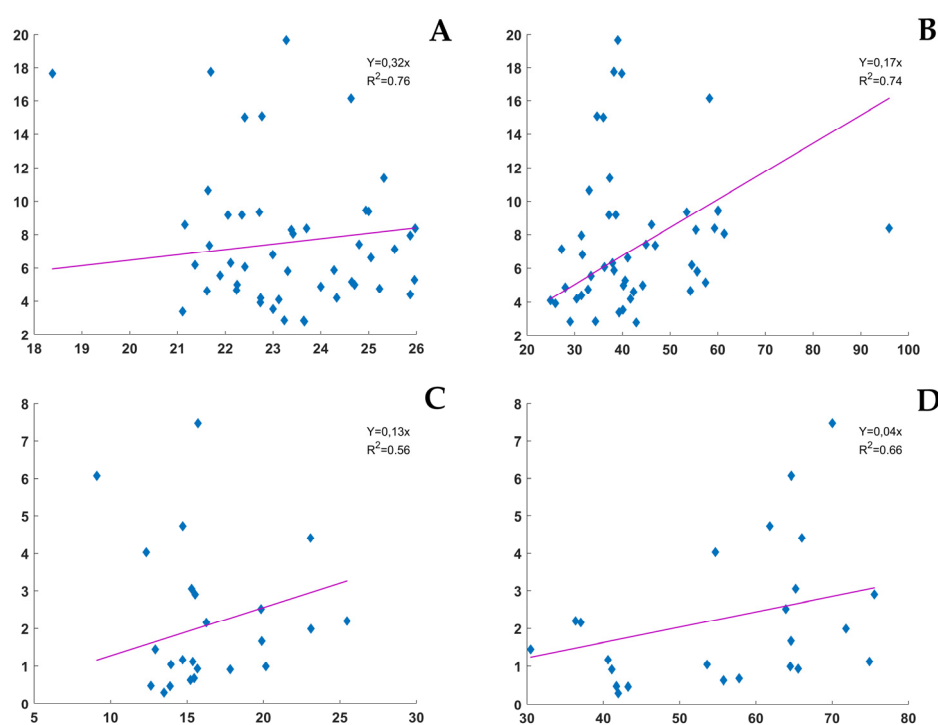


Figure 7. Correlation scatter plots between outdoor HCHO concentrations and meteorological parameters. A: T_{ind} vs $HCHO_{ind}$; B: RH_{ind} vs $HCHO_{ind}$; C: T_{out} vs $HCHO_{out}$; D: RH_{out} vs $HCHO_{out}$.

In detail, during the campaign a relevant influence of the monitored site by wind circulation has been observed. In Figure 8, the averaged concentrations of indoor and outdoor HCHO in each working room and outdoor wind speed gathered on wind direction are reported.

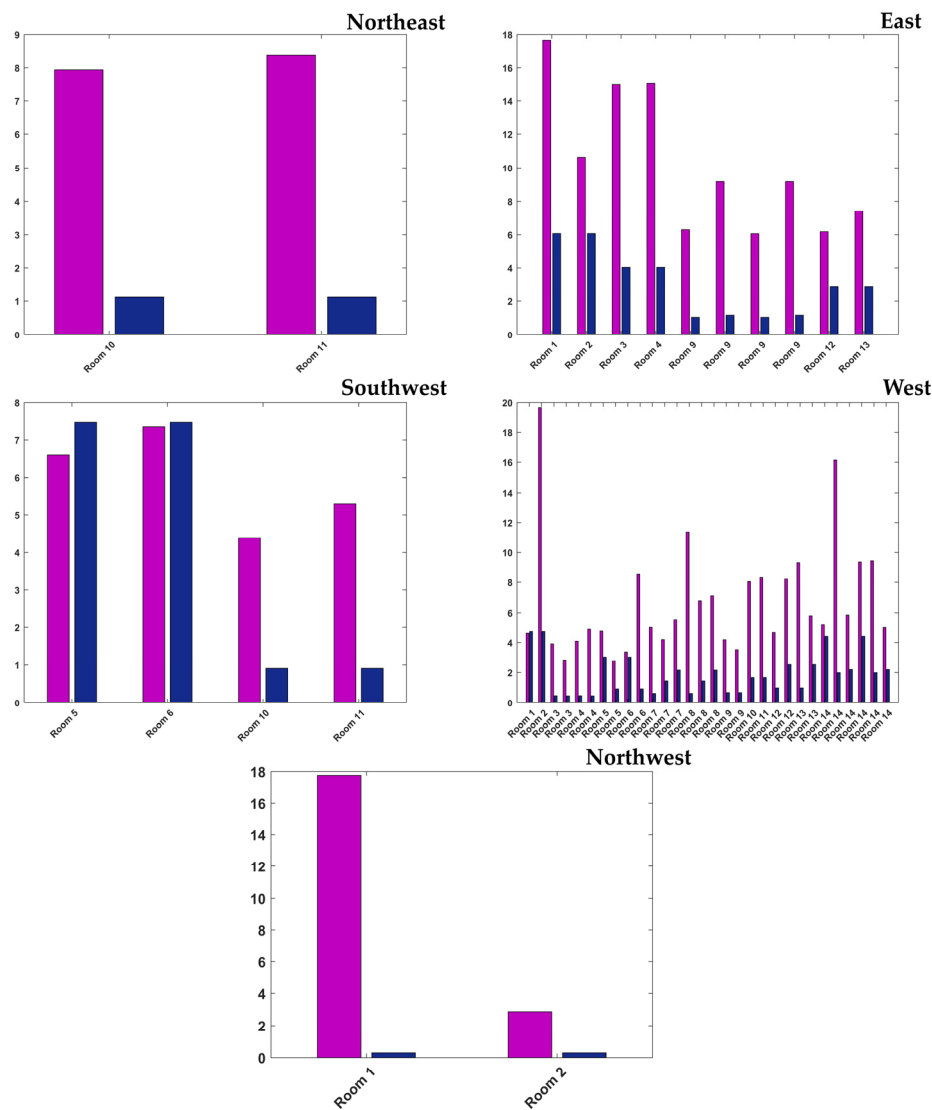


Figure 8. Correlations between outdoor/indoor formaldehyde and wind parameters by wind sector. Purple bars indicate indoor concentrations, while blue bars indicate outdoor values.

As already stated, indoor HCHO concentrations are always higher than outdoor mole fractions, however in case of E-NE wind corridors, such differences are amplified due to anthropic pollution. Details on the observed O/I (outdoor to indoor) ratios are in Figure 9.

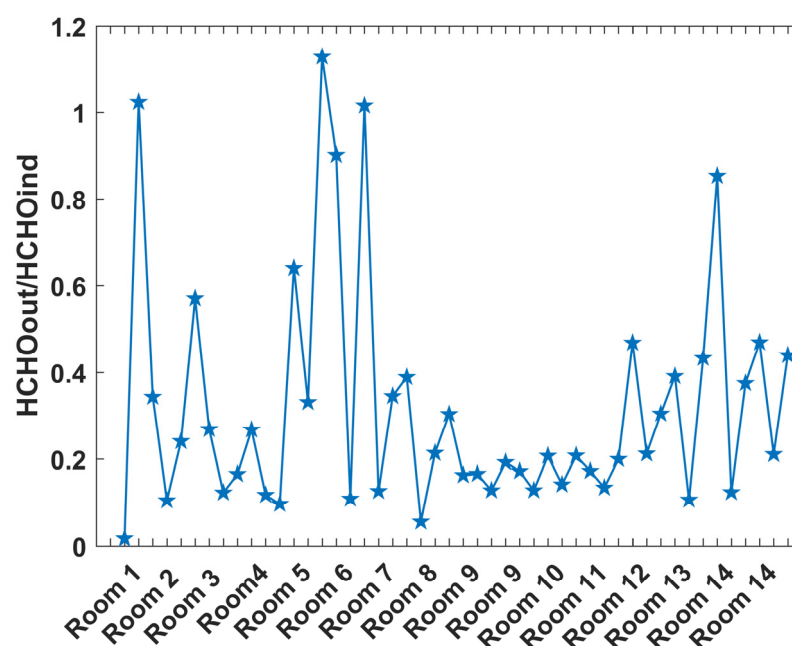


Figure 9. Outdoor to indoor (O/I) ratios of formaldehyde, per room.

The outdoor/indoor concentration ratio is commonly reported to be less than 1, indicating that indoor formaldehyde concentrations are typically higher than those found outdoors. Surveyed rooms generally have O/I values below the 1 threshold; rooms 1, 5, 6, 7 are close to this threshold, thus indicating similar outdoor and indoor FA concentrations.

5. Discussion

In the industrial area of Lamezia Terme (Calabria, Southern Italy), joint research by INAIL's DiMEILA and CNR's ISAC departments (Figure 1) assessed formaldehyde concentrations during a summer 2021 campaign by integrating satellite data with local measurements. This experimental campaign, performed during the 2021 summer season, is a first step towards the cross indoor/outdoor assessment of FA exposure hazards in Calabria. A proper evaluation of FA exposure is required, as atmospheric measurements in the region report notable wildfire emissions [80] which are among the sources of FA known in literature (Section 1).

In this work, satellite data from Sentinel-5P on atmospheric column have been integrated by local surface measurements of formaldehyde (HCHO, FA) and key meteorological parameters (temperature, wind speed and direction, relative humidity) (Figure 2) to assess the indoor and outdoor exposure to FA in areas not subject by continuous measurements (Figure 3). Indoor analyses have been performed on a per-room basis at the INAIL research center (Figure 4) in order to add a new degree of detail to the study.

The site where the campaign took place is located on the Tyrrhenian coast of Calabria, in the municipality of Lamezia Terme, and previous works on the site have shown the presence of well-established wind regimes dominated by breezes and prevailing W/NE corridors [73,74] which have a strong influence on the atmospheric concentration of greenhouse gases and pollutants observed at the local WMO/GAW station [81,82,87]. Prevailing wind regimes have been classified and used to determine the main corridors of air mass transport in order to test their influence on formaldehyde concentrations in the campaign (Figure 5).

From the W/NW sector, outdoor FA concentrations are lower due to seaside winds which are generally depleted in pollutants [81], although exceptions such as surface ozone (O_3) have been reported [82]. The W/SW sectors yield higher outdoor and indoor concentrations that we hereby attribute to orthopedic prosthetics manufacturing in that direction. Specifically, the W sub-sector

yields lower values compared to the SW sub-sector because wind speeds in the latter direction are lower and air masses can persist for a longer period of time, thus increasing the exposure and detection times. Overall, the correlation between concentrations and wind parameters (Figure 6) is in accordance with other studies performed at the WMO site on how local wind circulation affects surface observations of greenhouse gases and pollutants. These findings remark on the susceptibility of buildings to FA exposure in terms of orientation with respect to prevailing local wind regimes, and also add degrees of variability which are correlated with meteorological factors observed on a local scale, such as relative humidity and temperature (Figure 7).

Outdoor and indoor FA have shown an average correlation rate, thus indicating an exchange between the two environments. With respect to external relative humidity, FA shows a correlation. Indoor and outdoor RH values are also correlated, thus indicating the lack of AC in the surveyed rooms.

Research indicates that outdoor formaldehyde concentrations generally range from 5 to 30 $\mu\text{g}/\text{m}^3$, influenced by factors such as industrial activities, vehicular emissions, and meteorological conditions. Conversely, indoor levels frequently range from 20 to 100 $\mu\text{g}/\text{m}^3$, with notable peaks in environments where formaldehyde-emitting products are prevalent. The O/I ratio, defined as the ratio between outdoor and indoor FA concentrations observed in this study, shows the contribution of outdoor FA to observed indoor concentrations. An O/I ratio of 0.3, for example, indicates that 30% of indoor FA is attributable to outdoor origin, while the remaining 70% is due to indoor sources such as furniture. Furthermore, the O/I ratio can fluctuate based on ventilation practices, seasonal changes, and building (in this case, room) occupancy levels.

It is known from leading literature that predominant increase in indoor formaldehyde concentrations relative to outdoor levels is attributed to several factors (Section 1). Poor ventilation increases the indoor accumulation rate of FA due to reduces air exchange. In outdoor environments, air flows lead to dilution and dispersion. Indoor environments are characterized by a number of sources, ranging from building materials to household products used on a daily basis; smoking and cooking, which are typically human activities, also result in FA indoor releases.

Seasonal influences can also lead to changes in FA concentrations, as higher outdoor temperatures may trigger photochemical reactions capable of perturbing FA levels.

This study was based on a summer campaign, however it allowed to highlight patterns and the interplay of several factors: the O/I ratios shown in Figure 9 allow to determine the presence of rooms which are more likely to be exposed to FA hazard and rooms with such exposures (specifically, their orientation and position within the building) are correlated with wind directions and local wind circulation. In terms of urban planning and environmental/health protection, this finding is of interest as it adds new variables to general FA hazard assessments in the area.

A proper understanding of O/I levels on a per room scale are deemed significant for a proper assessment of the FA exposure hazard. As a confirmed carcinogen, FA should be monitored constantly, and concentration peaks require precise and immediate actions be taken to mitigate all related risks. The findings of this study show that gathering data in one spot within a building is not sufficient to determine the broad FA hazard, as individual rooms need to be considered, as well as their orientation with respect to prevailing winds. The findings shown in this study therefore constitute a new fundament upon which FA exposure hazards assessments should be based on.

6. Conclusions

A joint venture campaign performed by INAIL DiMEILA and CNR ISAC in the municipality of Lamezia Terme (Calabria, Southern Italy) exploited the presence of a WMO/GAW observatory located nearby a research center on insurance against accidents at work. Local meteorological data gathered at the WMO observation sites have been used in conjunction with the results of a campaign on indoor and outdoor formaldehyde (FA) concentrations to assess, for the first time, correlations between key meteorological parameters and FA exposure in outdoor and indoor environments. In addition to surface data, total column data from the Sentinel-5P satellite have been used to further assess correlations between the findings and third party data.

The campaign shows the correlation between indoor and outdoor FA, defined as an O/I ratio indicating the exchange between the two surveyed environments. The study was aimed at specific rooms within the INAL building and demonstrated the heterogeneity of FA exposure hazards. O/I values have been demonstrated to vary even in the context of the same building, above and below the O/I threshold of 1.

Furthermore, rooms have proved different degrees of susceptibility to FA exposure depending on their orientation with respect to prevailing wind circulation pattern, in accordance with previous research at the WMO site which showed well-defined correlations between wind patterns and the concentrations of greenhouse gases and other pollutants.

This study shows the importance of integrating, where available, data from other sources to complement indoor and outdoor FA assessments and provides new insights on regulations and policies that could be channeled towards the mitigation of the FA exposure risk in workplaces and similar environments.

Supplementary Materials: None.

Author Contributions: Conceptualization, E.B., M.V., and T.L.F.; methodology, E.B., M.V., M.S., P.S., and T.L.F.; software, T.L.F.; validation, E.B., M.V., M.S., P.S., L.M., and T.L.F.; formal analysis, E.B., M.V., M.S., P.S., L.M., and T.L.F.; investigation, E.B., M.V., M.S., P.S., L.M., and T.L.F.; data curation, E.B., M.V., P.S., L.M., and T.L.F.; writing—original draft preparation, E.B., M.V., M.S., P.S., F.D., and T.L.F.; writing—review and editing, E.B., M.V., M.S., P.S., L.M., F.D., and T.L.F.; visualization, F.D. and T.L.F.; supervision, E.B., M.V., and T.L.F.; funding acquisition, E.B., M.V., and T.L.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by INAIL (Italian National Institute for Insurance against Accidents at Work) and CNR-ISAC (National Research Council of Italy – Institute of Atmospheric Sciences and Climate).

Data Availability Statement: The datasets mentioned in this work are not readily available because they're currently being evaluated for ongoing research. Sentinel-5P data are accessible via the platforms linked in this paper.

Acknowledgments: The authors would like to acknowledge the support of Claudia Roberta Calidonna (PI of the Lamezia Terme WMO/GAW observation site) and Ivano Ammoscato (technical supervisor at the same WMO site).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Frankforter, G.B. On the Liberation of Formaldehyde Gas. *J. Am. Chem. Soc.* **1906**, *28*(10), 1512. <https://doi.org/10.1021/ja01976a031>.
2. Andersen, I.; Lundqvist, G.R.; Molhave, L. Formaldehyde in the home atmosphere. Proposed introduction of limits for airborne contaminants. *Ugeskrift for Læger* **1979**, *141*(14), 966-971.
3. Niemelä, R.; Vainio, H. Formaldehyde exposure in work and the general environment. Occurrence and possibilities for prevention. *Scand. J. Work Environ. Health* **1981**, *7*(2), 95-100. <https://doi.org/10.5271/sjweh.2554>.
4. Merchán, M.L.; De La Serna, J. Formadehyde as an indoor pollutant. *Toxicol. Environ. Chem.* **1986**, *13*(1-2), 17-25. <https://doi.org/10.1080/02772248609357168>.
5. Schachter, E.N.; Witek, T.J.; Tosun, T.; Leaderer, B.P.; Beck, G.J. A study of respiratory effects from exposure to 2 ppm formaldehyde in healthy subjects. *Arch. Environ. Health* **1986**, *41*(4), 229-239. <https://doi.org/10.1080/00039896.1986.9938338>.
6. Schmitz, H.; Hilgers, U.; Weidner, M. Assimilation and metabolism of formaldehyde by leaves appear unlikely to be of value for indoor air purification. *New Phytol.* **2000**, *147*(2), 307-315. <https://doi.org/10.1046/j.1469-8137.2000.00701.x>.
7. Gillett, K.W.; Kreibich, H.; Ayers, G.P. Measurement of indoor formaldehyde concentrations with a passive sampler. *Environ. Sci. Technol.* **2000**, *34*(10), 2051-2056. <https://doi.org/10.1021/es990929n>.
8. Paustenbach, D.; Alarie, Y.; Kulle, T.; Schachter, N.; Smith, R.; Swenberg, J.; Witschi, H.; Horowitz, S.B. A recommended occupational exposure limit for formaldehyde based on irritation. *J. Toxicol. Environ. Health* **1997**, *50*(3), 217-264. <https://doi.org/10.1080/009841097160465>.
9. Koeck, M.; Pichler-Semmelrock, F.P.; Schlacher, R. Formaldehyde – Study of indoor air pollution in Austria. *Cent. Eur. J. Public Health* **1997**, *5*(3), 127-130.
10. Chuah, Y.K.; Fu, Y.M.; Hung, C.C.; Tseng, P.C. Concentration variations of pollutants in a work week period of an office. *Build. Environ.* **1997**, *32*(6), 525-540. [https://doi.org/10.1016/S0360-1323\(97\)00018-8](https://doi.org/10.1016/S0360-1323(97)00018-8).

11. Hong, E.; Lee, E.; Kim, Y.; Oh, E.; Kim, Y.W.; Moon, K.W.; Choi, J.W.; Lee, J.; Roh, J. The correlations between oxidative stress markers and indoor volatile organic compounds among the general population in Ansan and Incheon cities, Korea. *Toxicol. Environ. Health. Sci.* **2009**, *1*, 37-48. <https://doi.org/10.1007/BF03216462>.
12. Hun, D.E.; Siegel, J.A.; Morandi, M.T.; Stock, T.H.; Corsi, R.L. Cancer risk disparities between Hispanic and non-hispanic white populations: The role of exposure to indoor air pollution. *Environ. Health Perspect.* **2009**, *117*(112), 1925-1931. <https://doi.org/10.1289/ehp.0900925>.
13. International Agency for Research on Cancer. IARC classifies formaldehyde as carcinogenic to humans. World Health Organization, Press Release n°153-2004.
14. Binazzi, A.; Mensi, C.; Miligi, L.; Di Marzio, D.; Zajacova, J.; Galli, P.; Camagni, A.; Calisti, R.; Balestri, A.; Murano, S.; et al. Exposures to IARC Carcinogenic Agents in Work Settings Not Traditionally Associated with Sinonasal Cancer Risk: The Experience of the Italian National Sinonasal Cancer Registry. *Int. J. Environ. Res. Public Health* **2021**, *18*, 12593. <https://doi.org/10.3390/ijerph182312593>.
15. Checkoway, H.; Dell, L.D.; Boffetta, P.; Gallagher, A.E.; Crawford, L.; Lees, P.J.S.; Mundt, K.A. Formaldehyde exposure and mortality risks from acute myeloid leukemia and other lymphohematopoietic malignancies in the US National Cancer Institute Cohort study of workers in formaldehyde industries. *JOEM* **2015**, *57*(7), 785–794. <https://doi.org/10.1097/JOM.0000000000000466>.
16. European Union. Commission Regulation (EU) No 605/2014 of 5 June 2014 amending, for the purposes of introducing hazard and precautionary statements in the Croatian language and its adaptation to technical and scientific progress, Regulation (EC) No 1272/2008 of the European Parliament and of the Council on classification, labelling and packaging of substances and mixtures Text with EEA relevance. <http://data.europa.eu/eli/reg/2014/605/oj> (accessed on 10 October 2024).
17. World Health Organization. WHO Guidelines for Indoor Air Quality: Selected Pollutants, **2010**, pp. 454.
18. Brasche, S.; Bischof, W. Daily time spent indoors in German homes – Baseline data for the assessment of indoor exposure of German occupants. *Int. J. Hyg. Environ. Health* **2005**, *208*(4), 247-253. <https://doi.org/10.1016/j.ijheh.2005.03.003>.
19. Schweizer, C.; Edwards, R.; Bayer-Oglesby, L.; Gauderman, W.J.; Ilacqua, V.; Jantunen, M.J.; Lai, H.K.; Nieuwenhuijsen, M.; Künzli, N. Indoor time–microenvironment–activity patterns in seven regions of Europe. *J. Expo. Sci. Environ. Epidemiol.* **2007**, *17*, 170–181. <https://doi.org/10.1038/sj.jes.7500490>.
20. Mannan, M.; Al-Ghamdi, S.G. Indoor air quality in buildings: a comprehensive review on the factors influencing air pollution in residential and commercial structure. *Int. J. Environ. Res. Public Health* **2021**, *18*(6), 3276. <https://doi.org/10.3390/ijerph18063276>.
21. Lucialli, P.; Marinello, S.; Pollini, E.; Scaringi, M.; Zauli Sajani, S.; Marchesi, S.; Cori, L. Indoor and outdoor concentrations of benzene, toluene, ethylbenzene and xylene in some Italian schools – evaluation of areas with different air pollution. *Atmos. Pollut. Res.* **2020**, *11*(11), 1998-2010. <https://doi.org/10.1016/j.apr.2020.08.007>.
22. Yu, C.W.F.; Crump, D.R. Testing for formaldehyde emission from wood-based products – A review. *Indoor Built Environ.* **1999**, *8*(5), 280-286. <https://doi.org/10.1159/000024655>.
23. Hodgson, A.T.; Beal, D.; McIlvaine, J.E.R. Sources of formaldehyde, other aldehydes and terpenes in a new manufactured house. *Indoor Air* **2002**, *12*(4), 235-242. <https://doi.org/10.1034/j.1600-0668.2002.01129.x>.
24. Li, S.; Banyasz, J.L.; Parrish, M.E.; Lyons-Hart, J.; Shafer, K.H. Formaldehyde in the gas phase of mainstream cigarette smoke. *J. Anal. Appl. Pyrol.* **2002**, *65*(2), 137-145. [https://doi.org/10.1016/S0165-2370\(01\)00185-1](https://doi.org/10.1016/S0165-2370(01)00185-1).
25. Salthammer, T.; Mentese, S.; Marutzky, R. Formaldehyde in the indoor environment. *Chem. Rev.* **2010**, *110*(4), 2536-2572. <https://doi.org/10.1021/cr800399g>.
26. Kelly, T.J.; Smith, D.L.; Satola, J. Emission rates of formaldehyde from materials and consumer products found in California homes. *Environ. Sci. Technol.* **1999**, *33*, 81-88. <https://doi.org/10.1021/es980592>.
27. Chen, X.; Li, F.; Liu, C.; Yang, J.; Zhang, J.; Peng, C. Monitoring, Human Health Risk Assessment and Optimized Management for Typical Pollutants in Indoor Air from Random Families of University Staff, Wuhan City, China. *Sustainability* **2017**, *9*(7), 1115. <https://doi.org/10.3390/su9071115>.
28. Widder, S.H.; Haselbach, L. Relationship among Concentrations of Indoor Air Contaminants, Their Sources, and Different Mitigation Strategies on Indoor Air Quality. *Sustainability* **2017**, *9*(7), 1149. <https://doi.org/10.3390/su9071149>.
29. Soltanpour, Z.; Mohammadian, Y.; Fakhri, Y. The exposure to formaldehyde in industries and health care centers: A systematic review and probabilistic health risk assessment. *Environ. Res.* **2022**, *204*(Part B), 112094. <https://doi.org/10.1016/j.envres.2021.112094>.
30. Protano, C.; Antonucci, A.; De Giorgi, A.; Zanni, S.; Mazzeo, E.; Cammalleri, V.; Fabiani, L.; Mastrantonio, R.; Muselli, M.; Mastrangeli, G.; Ursini, C.L.; Cavallo, D.; Poli, D.; Di Gennario, G.; De Palma, G.; Vitali, M. Exposure and Early Effect Biomarkers for Risk Assessment of Occupational Exposure to Formaldehyde: A Systematic Review. *Sustainability* **2024**, *16*(9), 3631. <https://doi.org/10.3390/su16093631>.

31. Parrish, D.D.; Ryerson, T.B.; Mellqvist, J.; Johansson, J.; Fried, A.; Richter, D.; Walega, J.G.; Washenfelder, R.A.; de Gouw, J.A.; Peischl, J.; Aikin, K.C.; McKeen, S.A.; Frost, G.J.; Fehsenfeld, F.C.; Herndon, S.C. Primary and secondary sources of formaldehyde in urban atmospheres: Houston Texas region. *Atmos. Chem. Phys.* **2012**, *12*, 3273–3288. <https://doi.org/10.5194/acp-12-3273-2012>.
32. Nogueira, T.; Dominutti, P.A.; De Carvalho, L.R.F.; Fornaro, A.; Andrade, M.D.F. Formaldehyde and acetaldehyde measurements in urban atmosphere impacted by the use of ethanol biofuel: Metropolitan Area of Sao Paulo (MASP), 2012-2013. *Fuel* **2014**, *134*, 505-513. <https://doi.org/10.1016/j.fuel.2014.05.091>.
33. Li, M.; Shao, M.; Li, L.-Y.; Lu, S.-H.; Chen, W.-T.; Wang, C. Quantifying the ambient formaldehyde sources utilizing tracers. *Chin. Chem. Lett.* **2014**, *25*, 1489–1491. <https://doi.org/10.1016/j.cclet.2014.07.001>.
34. Jung, S.; Kim, S.; Chung, T.; Hong, H.; Lee, S.; Lim, J. Emission Characteristics of Hazardous Air Pollutants from Medium-Duty Diesel Trucks Based on Driving Cycles. *Sustainability* **2021**, *13*(14), 7834. <https://doi.org/10.3390/su13147834>.
35. Giarracca, L.; Tran, L.-S.; Gosselin, S.; Hanoune, B.; Gasnot, L. Quantitative measurement of formaldehyde formed in combustion processes using gas chromatography analytical approach. *Combust. Sci. Technol.* **2023**, *195*(12), 2716-2731. <https://doi.org/10.1080/00102202.2022.2039644>.
36. Du, W.; Xie, H.; Li, J.; Guan, X.; Li, M.; Wang, H.; Wang, X.; Zhang, X.; Zhang, Q. The Emission Characteristics of VOCs and Environmental Health Risk Assessment in the Plywood Manufacturing Industry: A Case Study in Shandong Province. *Sustainability* **2024**, *16*(17), 7350. <https://doi.org/10.3390/su16177350>.
37. Goode, J.G.; Yokelson, R.J.; Ward, D.E.; Susott, R.A.; Babbitt, R.E.; Davies, M.A.; Hao, W.M. C₂H₂, HCN, NO, NH₃, HCOOH, CH₃COOH, HCHO, and CH₃OH in 1997 Alaskan biomass burning plumes by airborne Fourier transform infrared spectroscopy (AFTIR). *J. Geophys. Res. -Atmos* **2000**, *105*(D17), 22147-22166.
38. Sinha, P.; Hobbs, P.V.; Yokelson, R.J.; Blake, D.R.; Gao, S.; Kirchstetter, T.W. Emissions from miombo woodland and dambo grassland savanna fires. *J. Geophys. Res. -Atmos* **2004**, *109*(D11), D11305, 1-13. <https://doi.org/10.1029/2004JD004521>.
39. Na, K.; Cocker, D.R. Fine organic particle, formaldehyde, acetaldehyde concentrations under and after the influence of fire activity in the atmosphere of Riverside, California. *Environ. Res.* **2008**, *108*, 7-14. <https://doi.org/10.1016/j.envres.2008.04.004>.
40. Young, E.; Paton-Walsh, C. Emission Ratios of the Tropospheric Ozone Precursors Nitrogen Dioxide and Formaldehyde from Australia's Black Saturday Fires. *Atmosphere* **2011**, *2*(4), 617-632. <https://doi.org/10.3390/atmos2040617>.
41. Sitnov, S.A.; Mokhov, I.I. Formaldehyde and nitrogen dioxide in the atmosphere during summer weather extremes and wildfires in European Russia in 2010 and western Siberia in 2012. *Int. J. Remote Sens.* **2017**, *38*(14), 4086-4106. <https://doi.org/10.1080/01431161.2017.1312618>.
42. Efimova, N.V.; Rukavishnikov, V.S. Assessment of Smoke Pollution Caused by Wildfires in the Baikal Region (Russia). *Atmosphere* **2021**, *12*(12), 1542. <https://doi.org/10.3390/atmos12121542>.
43. Simmons, J.B.; Paton-Walsh, C.; Mouat, A.P.; Kaiser, J.; Humphries, R.S.; Keywood, M.; Griffith, D.W.T.; Sutresna, A.; Naylor, T.; Ramirez-Gamboa, J. Bushfire smoke plume composition and toxicological assessment from the 2019-2020 Australian Black Summer. *Air Qual. Atmos. Health* **2022**, *15*(11), 2067-2089. <https://doi.org/10.1007/s11869-022-01237-5>.
44. Vichi, F.; Bassani, C.; Ianniello, A.; Esposito, G.; Montagnoli, M.; Imperiali, A. Formaldehyde Continuous Monitoring at a Rural Station North of Rome: Appraisal of Local Sources Contribution and Meteorological Drivers. *Atmosphere* **2023**, *14*(12), 1833. <https://doi.org/10.3390/atmos14121833>.
45. Zhao, T.; Mao, J.; Ayazpour, Z.; González Abad, G.; Nowlan, C.R. Zheng, Y. Interannual variability of summertime formaldehyde (HCHO) vertical column density and its main drivers at northern high latitudes. *Atmos. Chem. Phys.* **2024**, *24*(10), 6105-6121. <https://doi.org/10.5194/acp-24-6105-2024>.
46. Adewuyi, Y.G.; Cho, S.-Y.; Tsay, R.-P.; Carmichael, G.R. Importance of formaldehyde in cloud chemistry. *Atmos. Environ.* **1984**, *18*(11), 2413-2420. [https://doi.org/10.1016/0004-6981\(84\)90011-8](https://doi.org/10.1016/0004-6981(84)90011-8).
47. Báez, A.P.; Padilla, H.G.; Belmont, R.D. Scavenging of atmospheric formaldehyde by wet precipitation. *Environ. Pollut.* **1993**, *79*(3), 271-275. [https://doi.org/10.1016/0269-7491\(93\)90100-3](https://doi.org/10.1016/0269-7491(93)90100-3).
48. Munger, J.W.; Jacob, D.J.; Danube, B.C.; Horowitz, L.W.; Keene, W.C.; Heikes, B.G. Formaldehyde, glyoxal, and methylglyoxal in air and cloudwater at a rural mountain site in central Virginia. *J. Geophys. Res. -Atmos.* **1995**, *100*(D5), 9325-9333. <https://doi.org/10.1029/95JD00508>.
49. Borbon, A.; Ruiz, M.; Bechara, J.; Aumont, B.; Chong, M.; Huntrieser, H.; Mari, C.; Reeves, C.E.; Scialom, G.; Hamburger, T.; Stark, H. Afif, C. Transport and chemistry of formaldehyde by mesoscale convective systems in West Africa during AMMA 2006. *J. Geophys. Res. -Atmos.* **2012**, *117*(12), D12301. <https://doi.org/10.1029/2011JD017121>.
50. Fried, A.; Barth, M.C.; Bela, M.; Weibring, P.; Richter, D.; Walega, J.; Li, Y.; Pickering, K.; Apel, E.; Hornbrook, R.; Hills, A.; Riener, D.D. Convective transport of formaldehyde to the upper troposphere and lower stratosphere and associated scavenging in thunderstorms over the central United States during the 2012DC3 study. *J. Geophys. Res. -Atmos.* **2016**, *121*(12), 7439-7460. <https://doi.org/10.1002/2015JD024477>.

51. Biswas, M.S.; Pandithurai, G.; Aslam, M.Y.; Patil, R.D.; Anilkumar, V.; Dudhambe, S.D.; Lerot, C.; De Smedt, I.; Van Roozendaal, M. Effects of boundary layer evolution on nitrogen dioxide (NO₂) and formaldehyde (HCHO) concentrations at a high-altitude observatory in western India. *Aerosol Air Qual. Res.* **2021**, *21*(3), 200193. <https://doi.org/10.4209/aaqr.2020.05.0193>.
52. Ceccarelli, C.; Maret, S.; Tielens, A.G.G.M.; Castets, A.; Caux, E. Theoretical H₂CO emission from protostellar envelopes. *Astronomy and Astrophysics* **2003**, *410*(2), 587-595. <https://doi.org/10.1051/0004-6361:20031243>.
53. Leroux, K.; Guillemin, J.-C.; Krim, L. Solid-state formation of CO and H₂CO via the CHOCHO + reaction. *Mon. Not. R. Astron. Soc.* **2020**, *491*, 289-301. <https://doi.org/10.1093/mnras/stz3051>.
54. Ramal-Olmedo, J.C.; Menor-Salván, C.A.; Fortenberry, R.C. Mechanisms for gas-phase molecular formation of neutral formaldehyde (H₂CO) in cold astrophysical regions. *Astron. Astrophys.* **2021**, *656*, A148. <https://doi.org/10.1051/0004-6361/202141616>.
55. Ibrahim, M.; Guillemin, J.-C.; Chaquin, P.; Markovits, A.; Krim, L. Formation of CO, CH₄, H₂CO and CH₃CHO through the H₂CCO + H surface reaction under interstellar conditions. *Physical Chemistry Chemical Physics* **2022**, *24*(38), 32245-23253. <https://doi.org/10.1039/D2CP02980D>.
56. Berglund, B.; Johansson, I.; Lindvall, T. A longitudinal study of air contaminants in a newly built preschool. *Environ. Int.* **1982**, *8*(1-6), 111-115. [https://doi.org/10.1016/0160-4120\(82\)90018-6](https://doi.org/10.1016/0160-4120(82)90018-6).
57. Lee, S.C.; Chang, M. Indoor air quality investigations at five classrooms. *Indoor Air* **1999**, *9*(2), 134-138. <https://doi.org/10.1111/j.1600-0668.1999.t01-2-00008.x>.
58. Khoder, M.I.; Shakour, A.A.; Farag, S.A.; Abdel Hameed, A.A. Indoor and outdoor formaldehyde concentrations in homes in residential areas in Greater Cairo. *J. Environ. Monit.* **2000**, *2*(2), 123-6. <https://doi.org/10.1039/a908756g>.
59. Pegas, P.N.; Evtyugina, M.G.; Alves, C.A.; Nunes, T.; Cerqueira, M.; Franchi, M.; Pio, C.; Almeida, S.M.; Freitas, M.D.C.; Outdoor/indoor air quality in primary schools in Lisbon: A preliminary study. *Quimica Nova* **2010**, *33*(5), 1145-1149. <https://doi.org/10.1590/S0100-40422010000500027>.
60. Goodman, N.B.; Wheeler, A.J.; Paevere, P.J.; Selleck, P.W.; Cheng, M.; Steinermann, A. Indoor volatile organic compounds at an Australian university. *Build. Environ.* **2018**, *135*, 344-351. <https://doi.org/10.1016/j.buildenv.2018.02.035>.
61. Huang, K.; Song, J.; Feng, G.; Chang, Q.; Jiang, B.; Wang, J.; Sun, W.; Li, H.; Wang, J.; Fang, X. Indoor air quality analysis of residential buildings in northeast China based on field measurements and longtime monitoring. *Build. Environ.* **2018**, *144*, 171-183. <https://doi.org/10.1016/j.buildenv.2018.08.022>.
62. Chang, T.; Wang, J.; Lu, J.; Shen, Z.; Huang, Y.; Sun, J.; Xu, H.; Wang, X.; Ren, D.; Cao, J. Evaluation of indoor air pollution during the decorating process and inhalation health risks in Xi'an, China: A case study. *Aerosol Air Qual. Res.* **2019**, *19*(4), 854-864. <https://doi.org/10.4209/aaqr.2018.07.0261>.
63. Liu, C.; Miao, X.; Li, J. Outdoor formaldehyde matters and substantially impacts indoor formaldehyde concentrations. *Build. Environ.* **2019**, *158*, 145-150. <https://doi.org/10.1016/j.buildenv.2019.05.007>.
64. Abelman, A.; McEwen, A.R.; Lotter, J.T.; Maskrey, J.R. Survey of 24-h personal formaldehyde exposures in geographically distributed urban office workers in the USA. *Environ. Sci. Pollut. Res. Int.* **2020**, *27*(14), 17250-27257. <https://doi.org/10.1007/s11356-020-08218-0>.
65. Kharel, M.; Chalise, S.; Chalise, B.; Sharma, K.R.; Gyawali, D.; Paudyal, H.; Neupane, B.B. Assessing volatile organic compound level in selected workplaces of Kathmandu Valley. *Heliyon* **2021**, *7*(11), e08262. <https://doi.org/10.1016/j.heliyon.2021.e08262>.
66. Jung, C.; Alqassimi, N.; El Samanoudy, G. The comparative analysis of the indoor air pollutants in occupied apartments at residential area and industrial area in Dubai, United Arab Emirates. *Front. Built Environ.* **2022**, *8*, 998858. <https://doi.org/10.3389/fbuil.2022.998858>.
67. European Chemicals Agency. Substance evaluation conclusion as required by REACH Article 48 and evaluation report for formaldehyde. <https://mail.isac.cnr.it/squirrelmail/src/webmail.php> (accessed on 13 October 2024).
68. Salthammer, T. Formaldehyde in the ambient atmosphere: from an indoor pollutant to an outdoor pollutant? *Angew. Chem. Int. Ed.* **2013**, *52*(12), 3320-3327. <https://doi.org/10.1002/anie.201205984>.
69. Zhang, H.; Zheng, Z.; Yu, T.; Liu, C.; Qian, H.; Li, J. Seasonal and diurnal patterns of outdoor formaldehyde and impacts on indoor environments and health. *Environ. Res.* **2022**, *205*, 112550. <https://doi.org/10.1016/j.envres.2021.112550>.
70. Zhu, L.; Jacob, D.J.; Keutsch, F.N.; Mickley, L.J.; Scheffe, R.; Strum, M.; González Abad, G.; Chance, K.; Yang, K.; Rappenglück, B.; Millet, D.B.; Baasandorj, M.; Jaeglé, L.; Shah, V. Formaldehyde (HCHO) as a hazardous air pollutant: Mapping surface air concentrations from satellite and inferring cancer risks in the United States. *Environ. Sci. Technol.* **2017**, *51*(10), 5650-5657. <https://doi.org/10.1021/acs.est.7b01356>.
71. Li, D.; Wang, S.; Xue, R.; Zhu, J.; Zhang, S.; Sun, Z.; Zhou, B. OMI-observed HCHO in Shanghai, China during 2010-2019 and ozone sensitivity inferred by improved HCHO/NO₂ ratio. *Atmos. Chem. Phys.* **2021**, *21*(20), 15447-15460. <https://doi.org/10.5194/acp-21-15447-2021>.

72. Butler, M.P.; Lauvaux, T.; Feng, S.; Liu, J.; Bowman, K.W.; Davis, K.J. Atmospheric Simulations of Total Column CO₂ Mole Fractions from Global to Mesoscale within the Carbon Monitoring System Flux Inversion Framework. *Atmosphere* **2020**, *11*(8), 787. <https://doi.org/10.3390/atmos11080787>.
73. Federico, S.; Pasqualoni, L.; De Leo, L.; Bellecci, C. A study of the breeze circulation during summer and fall 2008 in Calabria, Italy. *Atmos. Res.* **2010**, *97*(1-2), pgs. 1-13. <https://doi.org/10.1016/j.atmosres.2010.02.009>.
74. Federico, S.; Pasqualoni, L.; Sempreviva, A.M.; De Leo, L.; Avolio, E.; Calidonna, C.R.; Bellecci, C. The seasonal characteristics of the breeze circulation at a coastal Mediterranean site in South Italy. *Adv. Sci. Res.* **2010**, *4*, pgs. 47–56. <https://doi.org/10.5194/asr-4-47-2010>.
75. Gulli, D.; Avolio, E.; Calidonna, C.R.; Lo Feudo, T.; Torcasio, R.C.; Sempreviva, A.M. Two years of wind-lidar measurements at an Italian Mediterranean Coastal Site. In European Geosciences Union General Assembly 2017, EGU – Division Energy, Resources & Environment, ERE. *Energy Procedia* **2017**, *125*, 214–220. <https://doi.org/10.1016/j.egypro.2017.08.194>.
76. Avolio, E.; Federico, S.; Miglietta, M.M.; Lo Feudo, T.; Calidonna, C.R.; Sempreviva, A.M. Sensitivity analysis of WRF model PBL schemes in simulating boundary-layer variables in southern Italy: An experimental campaign. *Atmos. Res.* **2017**, *192*, 58–71. <https://doi.org/10.1016/j.atmosres.2017.04.003>.
77. Lo Feudo, T.; Calidonna, C.R.; Avolio, E.; Sempreviva, A.M. Study of the Vertical Structure of the Coastal Boundary Layer Integrating Surface Measurements and Ground-Based Remote Sensing. *Sensors* **2020**, *20*(22), 6516. <https://doi.org/10.3390/s20226516>.
78. Cristofanelli, P.; Busetto, M.; Calzolari, F.; Ammoscato, I.; Gulli, D.; Dinoi, A.; Calidonna, C.R.; Contini, D.; Sferlazzo, D.; Di Iorio, T.; Piacentino, S.; Marinoni, A.; Maione, M.; Bonasoni, P. Investigation of reactive gases and methane variability in the coastal boundary layer of the central Mediterranean basin. *Elem. Sci. Anth.* **2017**, *5*, 12. <https://doi.org/10.1525/elementa.216>.
79. Calidonna, C.R.; Avolio, E.; Gulli, D.; Ammoscato, I.; De Pino, M.; Donateo, A.; Lo Feudo, T. Five Years of Dust Episodes at the Southern Italy GAW Regional Coastal Mediterranean Observatory: Multisensors and Modeling Analysis. *Atmosphere* **2020**, *11*(5), 456. <https://doi.org/10.3390/atmos11050456>.
80. Malacaria, L.; Parise, D.; Lo Feudo, T.; Avolio, E.; Ammoscato, I.; Gulli, D.; Sinopoli, S.; Cristofanelli, P.; De Pino, M.; D'Amico, F.; Calidonna, C.R. Multiparameter detection of summer open fire emissions: the case study of GAW regional observatory of Lamezia Terme (Southern Italy). *Fire* **2024**, *7*(6), 198. <https://doi.org/10.3390/fire7060198>.
81. D'Amico, F.; Ammoscato, I.; Gulli, D.; Avolio, E.; Lo Feudo, T.; De Pino, M.; Cristofanelli, P.; Malacaria, L.; Parise, D.; Sinopoli, S.; De Benedetto, G.; Calidonna, C.R. Integrated analysis of methane cycles and trends at the WMO/GAW station of Lamezia Terme (Calabria, Southern Italy). *Atmosphere* **2024**, *15*(8), 946. <https://doi.org/10.3390/atmos15080946>.
82. D'Amico, F.; Gulli, D.; Lo Feudo, T.; Ammoscato, I.; Avolio, E.; De Pino, M.; Cristofanelli, P.; Busetto, M.; Malacaria, L.; Parise, D.; Sinopoli, S.; De Benedetto, G.; Calidonna, C.R. Cyclic and multi-year characterization of surface ozone at the WMO/GAW coastal station of Lamezia Terme (Calabria, Southern Italy): implications for local environment, cultural heritage, and human health. *Environments* **2024**, *11*(10), 227. <https://doi.org/10.3390/environments11100227>.
83. Donateo, A.; Lo Feudo, T.; Marinoni, A.; Dinoi, A.; Avolio, E.; Merico, E.; Calidonna, C.R.; Contini, D.; Bonasoni, P. Characterization of In Situ Aerosol Optical Properties at Three Observatories in the Central Mediterranean. *Atmosphere* **2018**, *9*(10), 369. <https://doi.org/10.3390/atmos9100369>.
84. Donateo, A.; Lo Feudo, T.; Marinoni, A.; Calidonna, C.R.; Contini, D.; Bonasoni, P. Long-term observations of aerosol optical properties at three GAW regional sites in the Central Mediterranean. *Atmos. Res.* **2020**, *241*, 104976. <https://doi.org/10.1016/j.atmosres.2020.104976>.
85. D'Amico, F.; Ammoscato, I.; Gulli, D.; Avolio, E.; Lo Feudo, T.; De Pino, M.; Cristofanelli, P.; Malacaria, L.; Parise, D.; Sinopoli, S.; De Benedetto, G.; Calidonna, C.R. Anthropogenic-induced variability of greenhouse gases and aerosols at the WMO/GAW coastal site of Lamezia Terme (Calabria, Southern Italy): towards a new method to assess the weekly distribution of gathered data. *Sustainability* **2024**, *16*(18), 8175. <https://doi.org/10.3390/su16188175>.
86. D'Amico, F.; Ammoscato, I.; Gulli, D.; Avolio, E.; Lo Feudo, T.; De Pino, M.; Cristofanelli, P.; Malacaria, L.; Parise, D.; Sinopoli, S.; De Benedetto, G.; Calidonna, C.R. Trends in CO, CO₂, CH₄, BC, and NO_x during the first 2020 COVID-19 lockdown: source insights from the WMO/GAW station of Lamezia Terme (Calabria, Southern Italy). *Sustainability* **2024**, *16*(18), 8229. <https://doi.org/10.3390/su16188229>.
87. D'Amico, F.; Calidonna, C.R.; Ammoscato, I.; Gulli, D.; Malacaria, L.; Sinopoli, S.; De Benedetto, G.; Lo Feudo, T. Peplospheric influences on local greenhouse gas and aerosol variability at the Lamezia Terme WMO/GAW regional station in Calabria, Southern Italy: a multiparameter investigation. **Under review at MDPI Sustainability.**
88. European Space Agency. Overview of Sentinel-5P Mission. <https://sentinel.esa.int/web/sentinel/missions/sentinel-5p> (accessed on 16 October 2024).

89. De Smedt, I.; Theys, N.; Yu, H.; Danckaert, T.; Lerot, C.; Compennolle, S.; Van Roozendaal, M.; Richter, A.; Hilboll, A.; Peters, E.; Pedernana, M.; Loyola, D.; Beirle, S.; Wagner, T.; Eskes, H.; van Geffen, J.; Folkert Boersma, K.; Veefkind, P. Algorithm theoretical baseline for formaldehyde retrievals from S5P TROPOMI and from the QA4ECV project. *Atmos. Meas. Tech.* **2018**, *11*(4), 2395–2426. <https://doi.org/10.5194/amt-11-2395-2018>.
90. De Smedt, I.; Theys, N.; Yu, H.; Vlietinck, J.; he Lerot, C.; Roozendaal, M.V. S5P/TROPOMI HCHO ATBD; Technical Report 2.3.0; BIRA-IASB: Uccle, Belgium, **2021**.
91. Copernicus. Sentinel-2 L2 database. <https://browser.dataspace.copernicus.eu> (accessed on 5 October 2024).
92. Apituley, A.; Pedernana, M.; Sneep, M.; Veefkind, J.P.; Loyola, D.H.O. Sentinel-5 Precursor/TROPOMI Level 2 Product User Manual Methane; Royal Netherlands Meteorological Institute: De Bilt, The Netherlands, **2022**.
93. De Smedt, I.; Eichmann, K.U.; Lambert, J.C.; Loyola, D.; Veefkind, J.P. S5P Mission Performance Centre Formaldehyde [L2 HCHO]Readme; Technical Report; BIRA-IASB: Uccle, Belgium, **2019**.
94. Vigouroux, C.; Langerock, B.; Augusto Bauer Aquino, C.; Blumenstock, T.; Cheng, Z.; De Mazière, M.; De Smedt, I.; Grutter, M.; Hannigan, J.W.; Jones, N.; Kivi, R.; Loyola, D.; Lutsch, E.; Mahieu, E.; Makarova, M.; Metzger, J.-M.; Morino, I.; Murata, I.; Nagahama, T.; Notholt, J.; Ortega, I.; Palm, M.; Pinardi, G.; Röhling, A.; Smale, D.; Stremme, W.; Strong, K.; Sussmann, R.; Té, Y.; van Roozendaal, M.; Wang, P.; Winkler, H. TROPOMI-Sentinel-5 Precursor formaldehyde validation using an extensive network of ground-based Fourier-transform infrared stations. *Atmos. Meas. Tech.* **2020**, *13*, 3751–3767. <https://doi.org/10.5194/amt-13-3751-2020>.
95. Spearman, C. The Proof and Measurement of Association between Two Things. *Am. J. Psychol.* **1904**, *15* (1), 72–101. <https://doi.org/10.2307/1412159>.
96. Schober, P.; Boer, C.; Schwarte, L.A. Correlation Coefficients: Appropriate Use and Interpretation. *Anesth. Analg.* **2018**, *126*(5), 1763–1768. <https://doi.org/10.1213/ane.0000000000002864>.
97. Myers, J.L.; Well, A.D.; Lorch, R.F. Jr. Research Design and Statistical Analysis (Third ed.). Routledge, New York, **2010**; pp. 832. <https://doi.org/10.4324/9780203726631>.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.