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Improving indoor air quality through an air purifier able to reduce aerosol particulate matter (PM) and volatile organic compounds (VOCs): Experimental results

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A R T I C L E I N F O

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A B S T R A C T

The adverse effects of fine particulate matter (PM) and many volatile organic compounds (VOCs) on human health are well known. Fine particles are, in fact, those most capable of penetrating in depth into the respiratory system. People spend most of their time indoors where concentrations of some pollutants are sometimes higher than outdoors. Therefore, there is the need to ensure a healthy indoor environment and for this purpose the use of an air purifier can be a valuable aid especially now since it was demonstrated that indoor air quality has a high impact on spreading of viral infections such as that due to SARS-COVID19. In this study, we tested a commercial system that can be used as an air purifier. In particular it was verified its efficiency in reducing concentrations of PM10 (particles with aerodynamic diameter less than 10 μm), PM2.5 (particles with aerodynamic diameter less than 2.5 μm), PM1 (particles with aerodynamic diameter less than 1 μm), and particles number in the range 0.3 μm–10 μm. Furthermore, its capacity in reducing VOCs concentration was also checked. PM measurements were carried out by means of a portable optical particle counter (OPC) instrument simulating the working conditions typical of a household environment. In particular we showed that the tested air purifier significantly reduced both PM10 and PM2.5 by 16.8 and 7.25 times respectively that corresponds to a reduction of about 90% and 80%. A clear reduction of VOCs concentrations was also observed since a decrease of over 50% of these gaseous substances was achieved.

1. Introduction

Indoor air quality (IAQ) (inside homes, schools, offices and workplaces in general) is of outmost importance because people spend most of their time, about 80%, in confined spaces. A large number of studies in the literature focus on the adverse effects that these pollutants

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can have on human health; here only some of the most recent ones are mentioned (Pan et al., 2018; Azuma et al., 2018; Yee et al., 2021; Guercio et al., 2021; Kampa and Castanas, 2008; Perera et al., 2019; Stabile et al., 2018; Buonanno et al., 2015; Zhang et al., 2019). There are also categories of people who are particularly sensitive such as children, elderly people and especially those with particular diseases for whom ensuring a healthy environment becomes even more important. For example, children who spent most of their time at school are continuously exposed to indoor pollutants (Salthammer et al., 2016; Zhang et al., 2019) even if particles mainly come from outdoor sources (Pacitto et al., 2020; Amato et al., 2014; Reche et al., 2014; Rivas et al., 2015). Several pollutants can be present in confined spaces (Lepore et al., 2010) and can both penetrate from outside and be emitted from specific indoor sources that are related to various activities (for example, cleaning, the use of products such as air fresheners, food cooking operations, fuel combustion, biomass burning, etc.). Among the pollutants that have the most adverse effects on human health we should mention both particulate matter (PM) and volatile organic compounds (VOCs).

As it is well known, legal limit values are fixed for various pollutants for ambient or outdoor environments. On the opposite, for indoor environments, there are only limit values for working places, while there are just some suggested objective values for indoor spaces. These recommendations and regulations usually refer to air change per hour, ACH, with the objective of lowering the CO_2 concentration below certain levels. For instance, indoor values of CO_2 above 1000 ppm are known to lower cognitive capabilities (Azuma et al., 2018). More in general WHO recommends limits for health-harmful concentrations of key air pollutants both outdoors and inside homes, taking into account the many scientific evidences. In 2010 a specific guideline for indoor air quality was edited by WHO (WHO, 2010). In U.S. the Environmental Protection Agency (EPA) has shown that the quality of indoor air is 5–10 times worse than outdoor.

Another important aspect should be considered as regards air quality, i.e. the pandemic due to a new virus, SARS-COVID19 that from Wuhan (China) in late 2019 spread rapidly allover in the world. Immediately scientist started to study its diffusion and the correlation with airborne particles focusing the attentions in particular on outdoor air (Setti et al., 2020a, 2020b; Linillos-Pradillo et al., 2021).

It has been widely demonstrated that indoor air quality has an important role in the effect of viral spreading as well as on fatal symptoms.

Indoor air quality has further become a topic of great interest since the SARS-Cov-2 pandemic occurred, due to the fact that in confined environments distances between people become even shorter. Public establishments (supermarkets, restaurants, shops, public offices, etc.) have immediately adopted safety measures to keep their distance and encourage air exchange where possible.

Indeed, it is needed to reduce airborne transmission of the infections in indoor environment where distances are lower in particular where gathering of people can occurs. Nevertheless, a much lower number of studies deals with the assessment of the virus diffusion in confined environments. A recent research addressed the issue of infection risk due to SARS-Cov-2 allowing to develop a model to be applied in enclosed spaces (Buonanno et al., 2020).

Therefore, recently, there has been an increased focus on validating devices, such that considered in the present study, that improve indoor air quality.

In order to guarantee an indoor healthy environment, air purification devices are often employed and the use of air filtration systems is spreading and rapidly growing contributing to improve air quality (Luo et al., 2015; Zhan et al., 2018; Fermo et al., 2020; Park et al., 2020).

PM10 (particles with aerodynamic diameter less than 10 μm), PM2.5 (particles with aerodynamic diameter less than 2.5 μm), and PM1 (particles with aerodynamic diameter less than 1 μm) are among the most harmful air pollutants together with gases such as ozone, nitrogen oxides, and sulfur oxides.

Ambient levels of PM2.5 exceeded the goal established by WHO at 75% of stations in the European Region in 2015, and exposure to PM reduces life expectancy by almost 1 year, mostly because of the increased risk of cardiovascular and respiratory diseases, and lung cancer (https://www.who.int/).

It is important pointing out that the chemical composition of PM, which has been widely investigated (Cuccia et al., 2013; Moroni et al., 2015; Atzei et al., 2014; Bozzetti et al., 2017; Cattaneo et al., 2016; Daellenbach et al., 2017; Bove et al., 2016), is another key factor that should be taken into account when the adverse health effects of the aerosol particulate matter on human health are considered. The chemical speciation of different size ranges and the distribution of the different components between the surface and the bulk of the particles should also be considered (Atzei et al., 2014). Nevertheless, such studies are normally carried out in outdoor environment. The most commonly controlled indoor pollutants include PM (at different sizes) and TVOC (total volatile organic compounds) as there is rather difficult to get a speciation of these. In order to guarantee a safe environment recently smart technologies based on different sensors were applied for the control of indoor air quality (Schieweck et al., 2018).

In this study, a commercial air purifier was tested in order to evaluate the capacity to reduce both PM and TVOCs concentrations. A far as PM monitoring, the evaluation has been carried out using a portable optical particle counter instrument and simulating household conditions. PM mass concentrations (PM10, PM2.5, PM1) and particle number concentration in 7 size-fractions between 0.3 μm and 10 μm were measured with this device. TVOCs were quantified by a specific sensor based on photoionization principle.ticis

2. Materials and methods

A commercial air purifier device, namely HYLA-EST device, was tested. This device is based on a water-bath filtration system through which the air is forced without the use of any other type of filter. In this way it is able to trap particles commonly present in household environments such as dust and biotic particles including allergens, directly into the water. It can be used both as a vacuum cleaner and an air purifier. A separator allows to return to the environment clean, water-washed air.

In order to validate the efficiency of the HYLA-EST device the measurements were performed inside a room of an apartment with a size of 4m × 4m × 2.5 m (corresponding to 40 m^3). Measurements were carried out on October 15, 2020.

2.1. PM measurement

In order to carry out PM measurements a P-DustMonit (Contec, Milan, Italy) portable unit was employed. The instrument is an optical particles counter (OPC) allowing continuous monitoring of particles concentration (size segregated) in the air. More details on the instrument are reported in Fermo et al. (Linillos-Pradillo et al., 2021). Instrument flow rate is 1 L/min, and the device is able to work in the temperature range 10 °C–40 °C. The instrument allows to measure the particle mass concentrations expressed as PM10, PM2.5 and PM1 in μg/m^3 (real time and simultaneously); furthermore, particles number concentration is also real time provided classifying the particles size into 7 dimensional classes starting from particles with diameter >0.3 μm up to particles with diameter <10 μm.

The measurements were carried out by placing the instrument inside a room of an apartment of about 40 m^3. The room was ventilated with outdoor air before starting the test, and it was expected that conditions were stabilized, i.e., that the trend of the curves relative to the three fractions of interest (PM10, PM2.5, and PM1) reached a plateau.

It is worth noting that optical particle counters like that one employed in the present study, are often used to track air quality and to quantify particles (Schieweck et al., 2018; Dinoi et al., 2017).

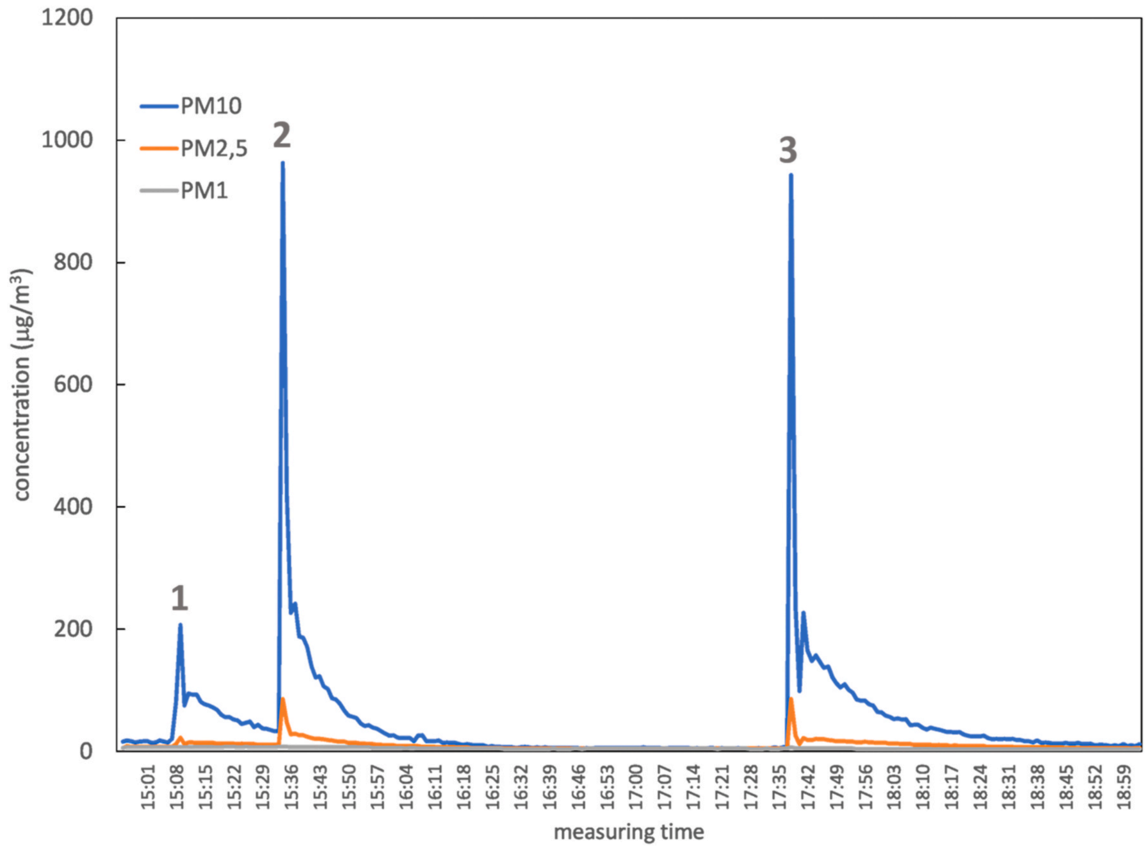

Fig. 1. PM10, PM2.5 and PM1concentration trends during the measurement period.

Furthermore, the high temporal resolution allows to investigate real time evolution of specific pollution events.

2.2. VOCs measurement

In order to measure the concentration of Total Volatile Organic Compounds (TVOC), Netpid instrument (Lab Service Analytics) was used. It is a VOCs sensor based on the photoionization system and capable of detecting a wide range of VOCs with a higher molecular weight than methane (which is therefore not detected). In order to validate the effectiveness of the instrument and its reproducibility, a series of preliminary tests were carried out dispersing in the room increasing VOCs concentrations. A commercial nail solvent was used at this purpose (further details on this point are reported further on in the text). The instrument was found to be reproducible. In addition, the detection limit is much lower than the minimum concentrations typically detectable in an indoor environment (between 0.1 and 0.2 ppm on average) while the maximum detectable concentration declared by the constructor is 3 ppm.

3. Results and discussion

The evaluation of the improvement of indoor air quality through the use of systems that filter air in different ways is a topic addressed in some studies reported in the literature (Fermo et al., 2020; Afshari et al., 2005; Kim and Lee, 2020).

Furthermore, because of the COVID-19 pandemic situation, more attention is paid to the issue of indoor air quality (Setti et al., 2020a, 2020b; Linillos-Pradillo et al., 2021; Buonanno et al., 2020) and for this reason the efficiency of air purification systems, such as that one validated in the present study, is being studied because these systems can make a real contribution to improving air quality in enclosed spaces.

The efficiency of this kind air purifier systems is tested using devices that include low-cost sensors, smart sensors or optical particles counters for particulate matter detection (Fermo et al., 2020; Kim and Lee, 2020; Owczarek et al., 2020).

In order to evaluate the effectiveness of the air purifier considered in this study in reducing PM and volatile organic compounds (VOCs) concentration in a typical household environment, a series of measurements were carried out evaluating the concentration of both PM and VOCs before switching on the device and during its operation. For this purpose, pollutants were artificially introduced into the room by some experiments during which some dust was dispersed in the room and VOCs were introduced, as previously reported.

3.1. Measurement of the ability to reduce concentrations of atmospheric particulate matter (PM)

In order to evaluate the ability of the air purifier to reduce atmospheric particulate matter concentrations, the background concentrations present in the test room were initially measured and 18 μg/m^3 and 7 μg/m^3 were registered for PM10 and PM2.5, respectively (as average values measured after 20 min of stabilization of the PM concentrations). As it is known, for indoor environments there aren't threshold values notwithstanding people spend most of their time in confined spaces. In some cases, as for example for the classrooms, suggested guidelines values are reported (Salthammer et al., 2016; WHO, 2006) such as 20 μg/m^3 and 10 μg/m^3 for PM10 and PM2.5, respectively. It is worth noting that the household environment selected for the test performed in the present study was characterized by quite low particulate matter concentrations of the order of the suggested indoor limits for PM10 and PM2.5. In particular, the values registered for PM2.5 are in good agreement with what reported by Jeong et al. (2019). In order to assess the efficiency of the air purifier, PM was artificially introduced in the

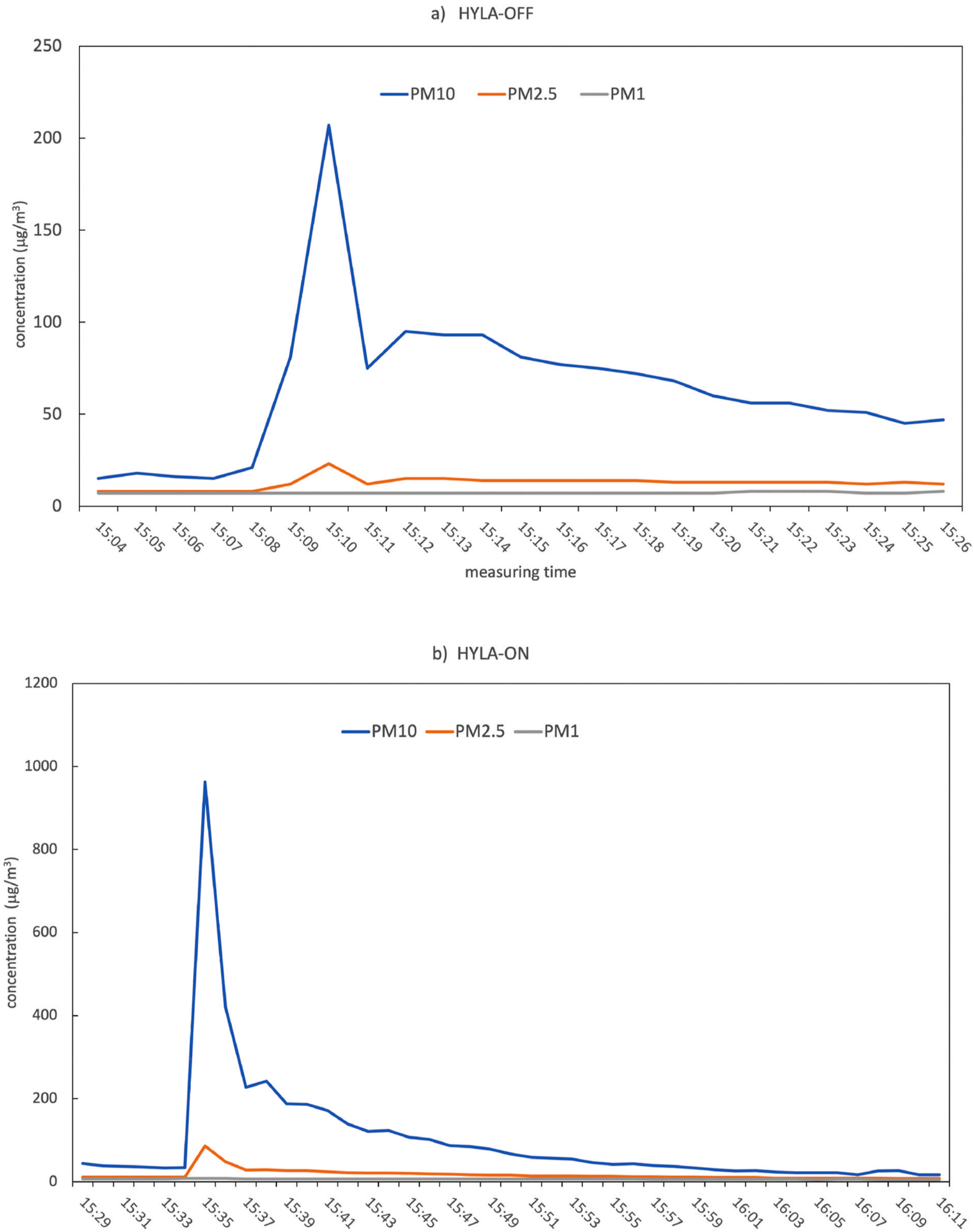

Fig. 2. PM concentration with the HYLA device switched off (2a) and on (2 b).

room in order to increase its concentration. By means of a fan, some dust contained in a plastic bag was dispersed in the air to obtain the desired increase of PM values, as reported in Fig. 1. In this way the peaks observable in Fig. 1 were obtained. In correspondence to the first peak (at 15:04 p.m., peak 1 in Fig. 1) a PM10 concentration of about 200 μg/m^3 was reached. It is worth noting that the HYLA device was switched off during this first experiment. Then, the test was repeated (at 15:34 p.m.) suspending a dust amount corresponding to 963 μg/m^3 as PM10 value. This second test was performed with the HYLA device switched on just after having dispersed the powder, waiting until the initial PM concentrations conditions were restored. The third test was performed trying to suspend a quantity of powder similar to the previous one, in this case 943 mg/m^3, but this time the device was switched off. Only PM10 and PM2.5 were considered since PM1 concentration was too low.

On the base of the slope of the curves corresponding to the

Table 1
Parameters related to the calculation of S for PM10 fraction.

HYLA OFF		
Δt (10 min)	C (μg/m³)	S
15:11	75	1,9
15:21	56	
HYLA ON		
Δt (10 min)	C (μg/m³)	S
15:37	421	31,9
15:47	102	

Table 2
Parameters related to the calculation of S for PM2.5 fraction.

HYLA OFF		
Δt (2 min)	C (μg/m³)	S
15:10	23	4,0
15:12	15	
HYLA ON		
Δt (2 min)	C (μg/m³)	S
15:35	86	29,0
15:37	28	

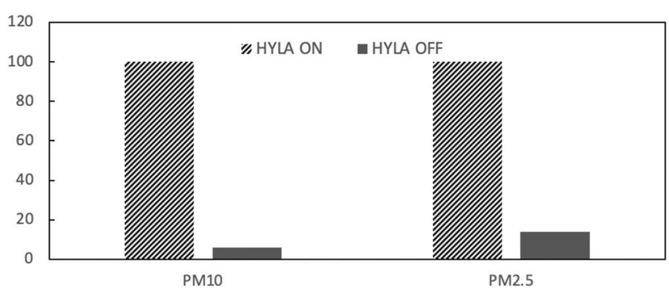

Fig. 3. Relative efficiency of the HYLA air purifier in reducing PM10 and PM.2 with respect to natural particulate matter deposition.

descending concentration of PM, the efficiency of the air purifier in reducing both PM10 and PM2.5 was estimated and compared what would happen when the particles, in this case the dust resuspended in the room, normally settle. 10 and 2 min were chosen as laying time for the evaluation of the decrease in particle concentration of PM10 and PM2.5, respectively. Ultimately, the slopes of the curve in Fig. 2a indicating the evolution to recover the initial conditions when the device was switched off (first peak in Fig. 2a which corresponds to peak 1 in Fig. 1) was compared with that obtained when the device was switched on (first peak in Fig. 2b which corresponds to peak 2 in Fig. 1). The comparison was quantified calculating the parameter S (slope), expressed as:

$$S = \Delta C/\Delta t$$

where:

ΔC = variation of PM concentration in μg/m³ in the time interval
Δt = interval time

The calculation was carried out for both PM10 and PM2.5, considering the first and the second peak corresponding to the device off and on, respectively. The results obtained are reported in Tables 1 and 2.

As far as PM10, accordingly to the values shown in Table 1, the value of S parameter was considerably higher when the instrument was turned on than off. The ratio between the two values is equal to 16.8, indicating that HYLA system is 16.8 times more efficient in the reduction of PM10 concentration compared to simple dust settlement. As far as PM2.5 data are concerned (Table 2), the value of S parameter was also considerably higher with the HYLA device was on, compared to the base case. The ratio between the two values in this case is 7.25, i.e. HYLA system is 7.25 times more efficient in the reduction of PM2.5 concentrations compared to simple dust deposition.

For sake of clarity a recalculation of S parameters was performed, setting the slopes obtained with the device on equal to 100. The results obtained are reported in Fig. 3, clearly highlighting high efficiency of the air purifier (the uncertainty was not calculated and the results shown are those obtained from the PM trends reported in Fig. 1). This corresponds to a decrease of about 90% for PM10 and about 80% for PM 2.5. These values are in accordance with what reported by Zhan et al. (2018) using air filtration devices.

Moreover, it was observed that the HYLA device allows to reach the PM values initially present in the room in 20 min, starting from very high PM10 concentrations. In absence of the device and in the same conditions,1 h would be necessary to restore the initial conditions as observable from Fig. 1.

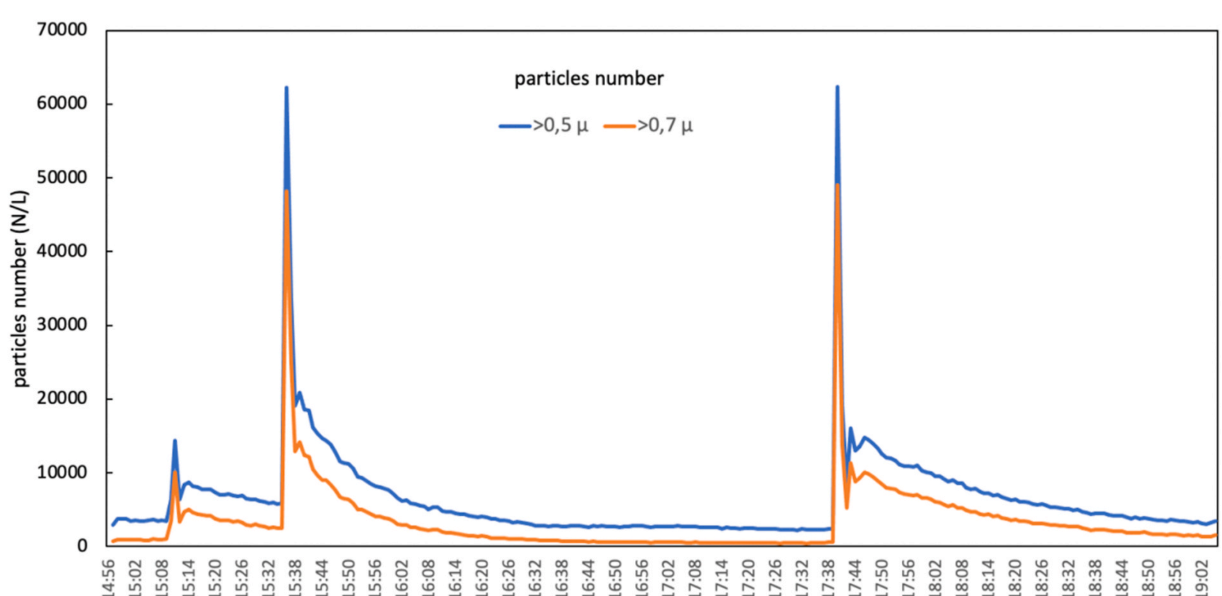

Fig. 4. Particles number concentration during the measuring period (N/L = number of particles per liter).

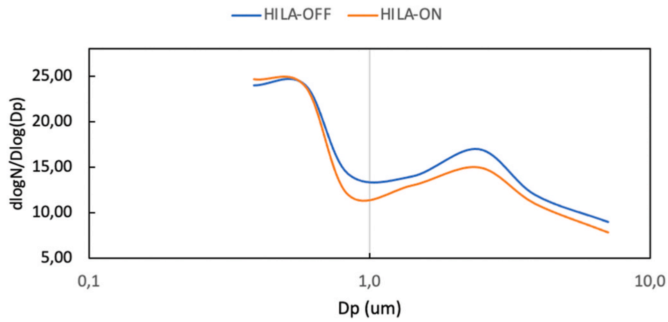

Fig. 5. Particle number distribution calculated as dlogN/dlog (Dp).

Fig. 4 shows the trend of the particles number (expressed as N/L) relative to the two fractions containing the finest particles, namely those with aerodynamic diameter greater than 0.5 μm and 0.7 μm. It can be observed that the effect is more pronounced in correspondence to the peak recorded at 15:36, i.e. with the HYLA device switched on (Fig. 2b).

In order to asses particles number during the two experiment with the instrument switched on or off (in this case peak 2 and 3 of Fig. 1 were considered), the curves dlogN/dlog (Dp) were obtained starting from the particles distribution over the 7 dimensional classes (as shown in Fig. 5). N represents the particle number within each class (namely particle with diameter 0.3–05 μm, 0.5-0-7 μm, 0.7–1 μm, 1–2 μm, 2–3 μm, 3–5 μm, 5–10 μm) while Dp represent the particle diameter. It is worth noting how an evident decrease of particles number in the fine fraction is observable in particular in the size range 0.7–2.5 μm. This represents an important result being the fine fraction the most dangerous for human health. In fact, the finer fraction is able to penetrate up to the pulmonary alveoli.

3.2. Measurement of the device ability to reduce TVOC concentrations in air

As for the TVOCs only suggested guideline values are reported; for example, inside classrooms it is recommend to stay below a threshold value of 1000 ppb (Salthammer et al., 2016).

To evaluate the ability of HYLA to reduce the concentration of TVOC in the air, a series of experiments were carried out by introducing a volatile organic compound, such as the common nail solvent, in the household environment.

The solvent bottle was opened for short or longer periods of time as described below. The bottle was placed at a distance of about 30 cm from the detector.

Fig. 6 shows the entire trend of TVOC acquired during the measurement period (performed in the time frame 5:34–19:10 on October 15, 2020).

The Netpid instrument for VOC analysis was initially switched on and stabilized. The average value of TVOC concentration in the room, when the HYLA device was not working, was about 0.2 ppm.

Table 3 reports the peaks shown in Figs. 6 and 7 and detected during the measurement (Fig. 7 represents an expanded zone of Fig. 7). For each peak, the exposure time to the nail solvent, the intensity of the peak and if HYLA device was on or off, is specified.

The first peak is relative to an exposure time of 15 s with the device off (the test was then repeated obtaining a peak of equal intensity, peak 2); then the test was repeated with the same exposure time but with the HYLA system on (peak 3): this has led to an evident reduction of the intensity that is about a half of the previous one.

Subsequently, a prolonged exposure time of 30 min (peak 4) was chosen to obtain a very intense broad peak with the instrument off (out of scale). At 12:55 a.m., the HYLA system was turned on and a clear reduction of the peak was observed (green arrow in Fig. 7). At 1:25 pm, after the signal stabilized and keeping the device on, a new exposure was made for a period of 30 min (peak 5).

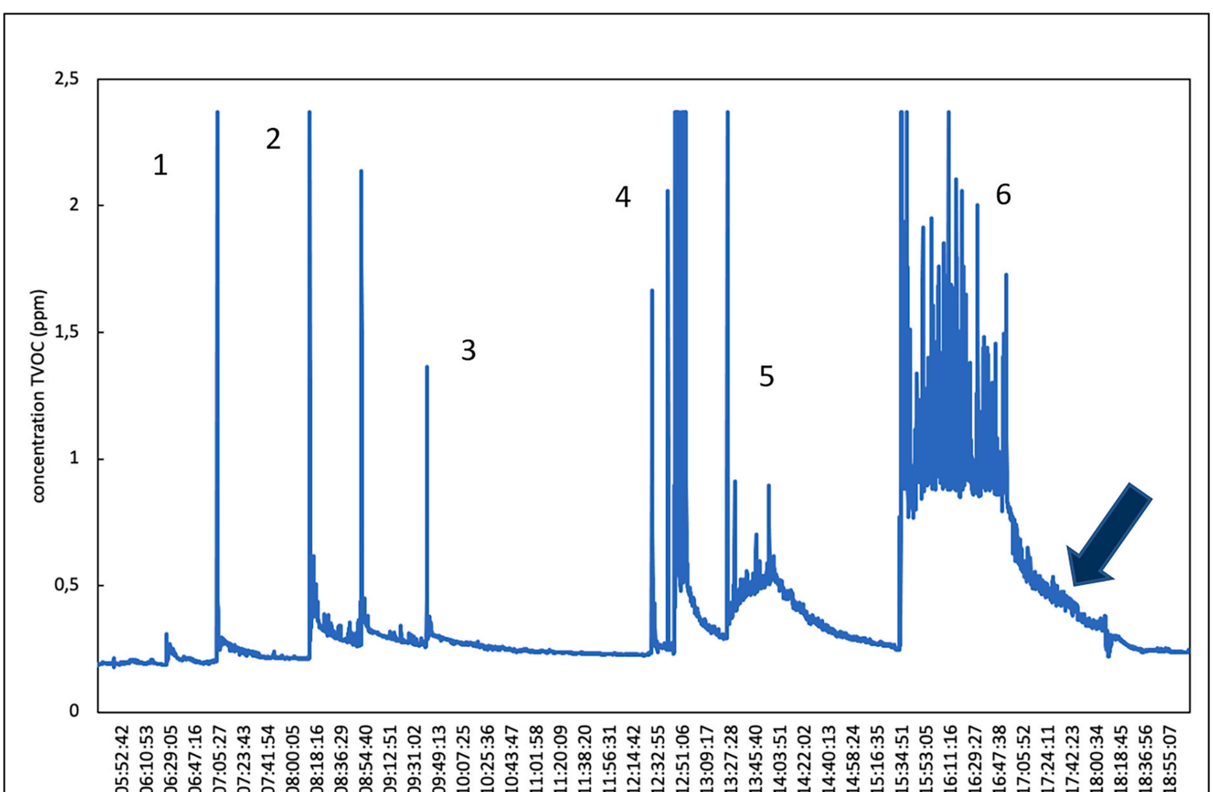

Fig. 6. TVOC concentration during the experiment (ppm).

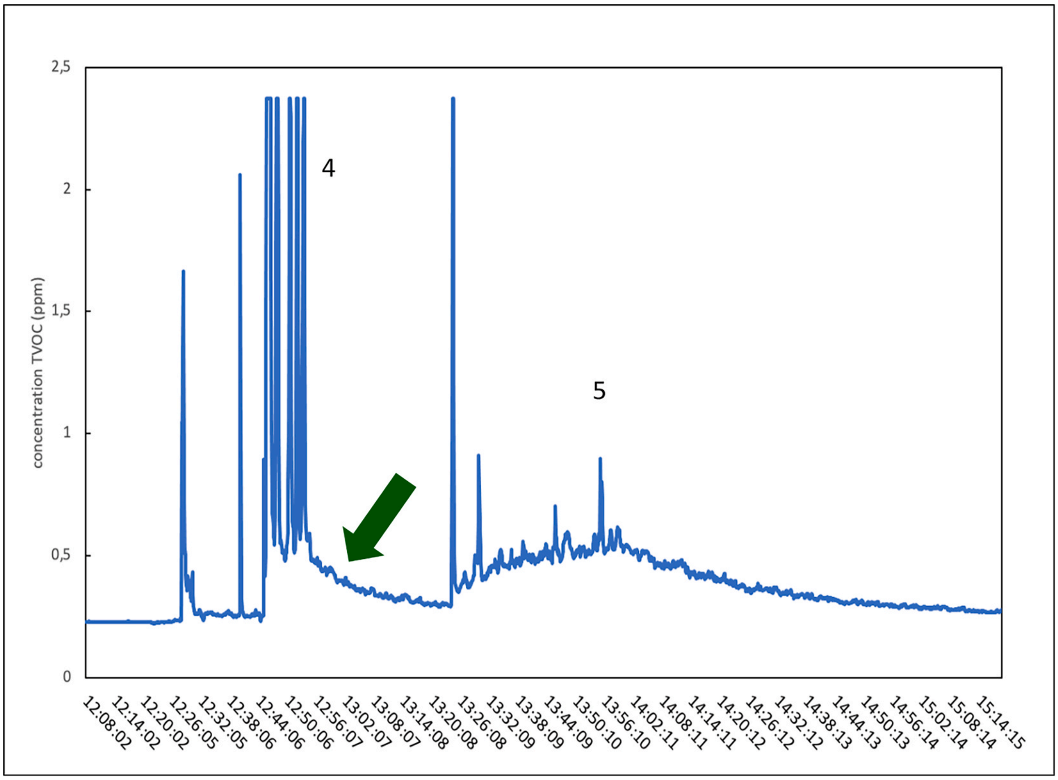

Fig. 7. TVOC concentrations during the experiment (ppm): detail of Fig. 6.

Table 3
Peak concentration (ppm) recorded by the Netpid instrument at successive time intervals and for different exposure times of the nail solvent; for peaks 4, 5 and 6 the intensity is not reported since they were out of scale.

Peak	Exposure time (s)	Peak intensity (ppm)	Operation device
1	15 s	2,37	OFF
2	15 s	2,37	OFF
3	15 s	1,36	ON
4	30 min (12.25–12.55)	broad peak	OFF
5	30 min (13.25–13.55)	broad peak	ON
6	1 h (15.30–16.30)	broad peak	OFF

Contrary to peak 4, in this case TVOCs intensity was lower with only one intense initial signal , demonstrating that HYLA is very efficient in reducing TVOCs.

Finally, an exposure time of 1 h was used to significantly increase the concentration of TVOCs in the room obtaining the broad signal indicated with 6 in Fig. 6 (with HYLA off). It is interesting to note that after 16:30, the concentration remains high, even if no additional VOCs are introduced in the room. At 16:48 the device was then turned on. In about 2 h, the signal reached the initial value (see the area indicated with the blue arrow in Fig. 6). Considering peak 2 and peak 3 of Table 3, it can be observed how a reduction of intensity over 40% is achieved.

4. Conclusions

On the basis of the tests carried out with regard to PM and VOCs reduction, it can be concluded that HYLA-EST device is effective both in the reduction of airborne particles concentrations and VOCs levels. In particular, an improvement of 16.8 and 7.25 times was observed for efficiency in reducing PM10 and PM2.5, respectively. This corresponds to a decrease of about 90% and 80% of PM10 and PM2.5, respectively. For household indoor environments with VOCs concentrations of the order of hundreds of ppb up to more than 1 ppm, a reduction of about 40% was reached by using the HYLA device as air purifier. Moreover, observing the trend relative to the concentration of VOCs intentionally added into the environment, it was observed that the device allows to restore the initial VOCs concentration in less than 2 h. Without the air purifier, the concentration would remain high reaching a plateau.

It can therefore be stated that HYLA-EST device can be used for the improvement of the indoor air quality, with regard the reduction of both airborne particles and volatile organic compounds, that may be present as pollutants emitted by various domestic activities such as, for example, cleaning operation, cooking of food, personal cleanliness, beauty products use, etc.

Also considering the need for improved indoor air quality in relation to the spreading of COVID-19 pandemic, air purifier systems could be successfully applied in particularly crowded and critical environments (for example schools or waiting rooms in doctors' surgeries and so on).

Moreover, a clear reduction in particles number, especially in the fine fraction, was observed during the device functioning and this fact has a positive impact on indoor air quality being the finer particles those that penetrate into the pulmonary alveoli.

Disclosures

This work has been carried out as voluntary independent scientific assessment of devices' efficacy in the frame of institutional activities of the Italian Society of Environmental Medicine (SIMA).

Credit author statement

Conceptualization, Paola Fermo and Alessandro Miani; methodology, Paola Fermo; validation, Paola Fermo; formal analysis, Paola Fermo; data curation, Paola Fermo, Begoña Artíñano, Alessandro Parente, Gianluca Di Tanna, Valeria Comite, Gian Luigi De Gennaro; writing—original draft preparation, Paola Fermo; writing—review and editing, Paola Fermo, Begoña Artíñano, Gian Luigi De Gennaro, Antonio Marco Pantaleo, Alessandro Parente' Fiorella Battaglia, Elena Colicino,

Gianluca Di Tanna, Andouglas Goncalves da Silva Junior, Igor Gadelha Pereira, Gabriel Santos Garcia, Luiz Marcos Garcia Goncalves, Valeria Comite; project administration, Paola Fermo and Alessandro Miani; all authors have read and agree to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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