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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Abstract: The adverse effects of fine particulate matter and many volatile organic substances 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 particle number in the range 0.3 μm -10 μm. Furthermore, its capacity in reducing VOCs (Volatile Organic Compounds) 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 over 90% and 80%. A clear reduction of VOCs concentrations was also observed since a decrease of over 50% of these gaseous substances was achieved.

Keywords: air cleaner; particulate matter; indoor air quality

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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 can have on human health, here only some of the most recent ones are mentioned [1-8]. 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 [9] even if particles mainly come from outdoor sources [10-13]. Several pollutants can be present in confined spaces [14] 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 environments, while there are just some suggested objective values for indoor spaces. In 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, values of CO_2 above 1000 ppm indoor are known to lower cognitive capabilities [2]. 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 [15]. In U.S. the Environmental Protection Agency (EPA) has shown that the quality of indoor air is 5–10 times worse than outdoor.

The neglected topic of indoor air quality has been extremely attentioned due to the current COVID-19 pandemic originated by the worldwide spreading of new coronavirus SARS-COV2 starting from Wuhan (China) in late 2019. It was immediately clear to scientists who studied SARS-COV2 diffusion the correlation with airborne particles both outdoor and indoor [16-18]. It has been widely demonstrated that indoor air quality has an important role in the coronavirus spreading as well as on increasing viral load possibly leading to lethal symptoms. Indoor air quality in confined environments represents a challenge as it seems to be even more crucial than maintaining distance between people. Public places such as supermarkets, restaurants, shops, offices etc. have immediately adopted safety measures to keep social distance and encourage air exchange where possible. Indeed, these measures are supposed to reduce airborne transmission of the virus in indoor environments where distances are lower. However, few studies have specifically assessed the patters of SARS-COV2 diffusion in indoor environments. A recent research addressed the issue of infection risk due to SARS-Cov-2 in the perspective of developing a model to be applied in indoor environments [19]. At the same time, an increasing interest has raised about assessment of devices and technologies that can improve indoor air quality, such that considered in the present study.

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 [20-22].

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 [24-30], 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 [26]. 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 [31].
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.

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 4mx4mx2.5m (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. [18]. 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, particle 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 particle with diameter of <10 μm.

The measurements were carried out by placing the instrument inside a room of an apartment measuring 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 [31-32]. 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 [22, 33, 34].

Furthermore, because of the COVID-19 pandemic situation, more attention is paid to the issue of indoor air quality [16-19] 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 [22, 34, 36].

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 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 minutes 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 [9, 37] 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 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. [38]. In order to assess the efficiency of the air purifier, PM was artificially introduced in the room. By means of a fan, some dust contained in a plastic bag was dispersed in the air to obtain the desired increase of PM concentration, as reported in Figure 1. In this way the peaks observable in Figure 1 were obtained. In correspondence to the first peak (at 15:04 pm, peak 1 in Figure. 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 pm) suspending a dust amount corresponding to 963 μg/m^3. as PM10 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 with 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 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 settled. Ten and two minutes 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 Figure 2 indicating the evolution to recover the initial conditions when the device was switched off (first peak in Figure 2a which corresponds to peak 1 in Figure 1) was compared with that obtained when the device was switched on (second peak in Figure 2 which corresponds to peak 2 in Figure 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/m[3] 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 Table 1and 3. In figures 2a and 2b, an enlargement of the first and the second peak is shown.

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	

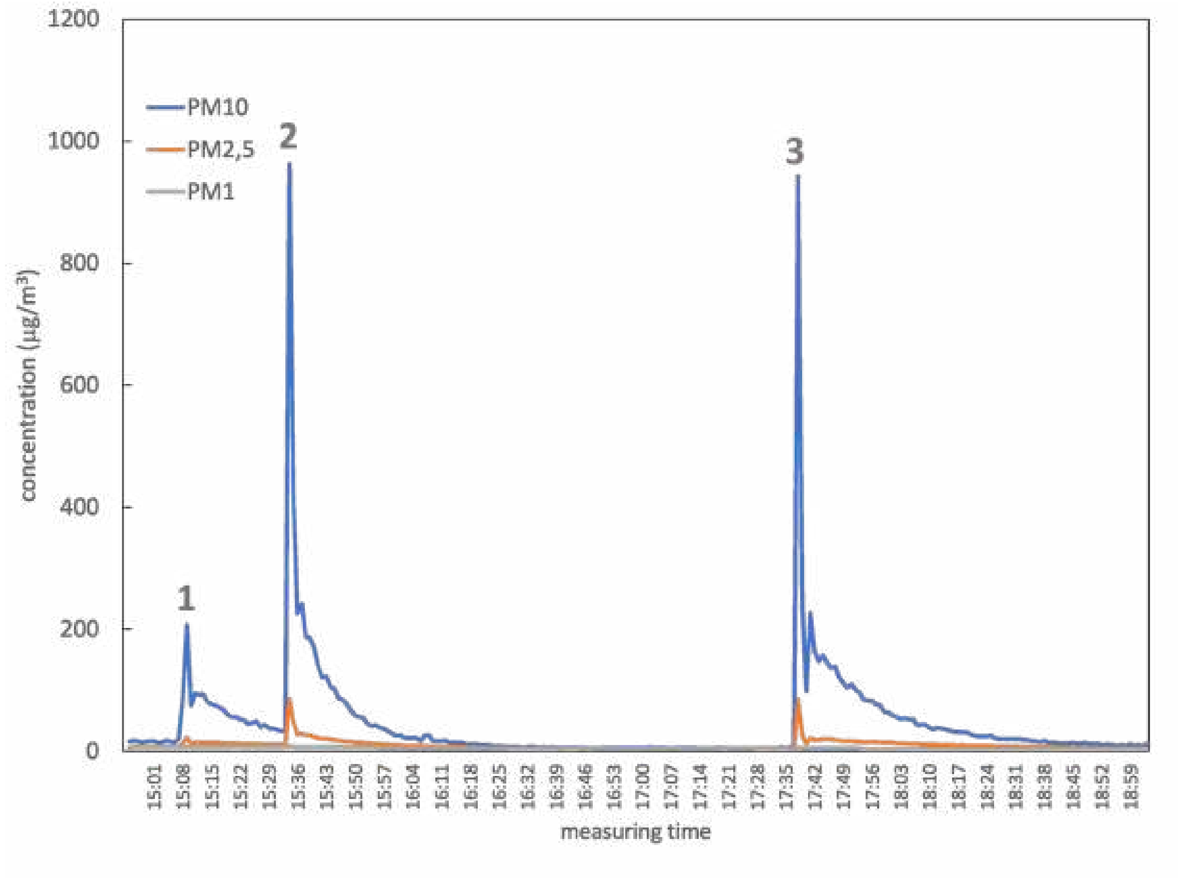

Figure 1. PM10, PM2.5 and PM1concentration trends during the measurement period.

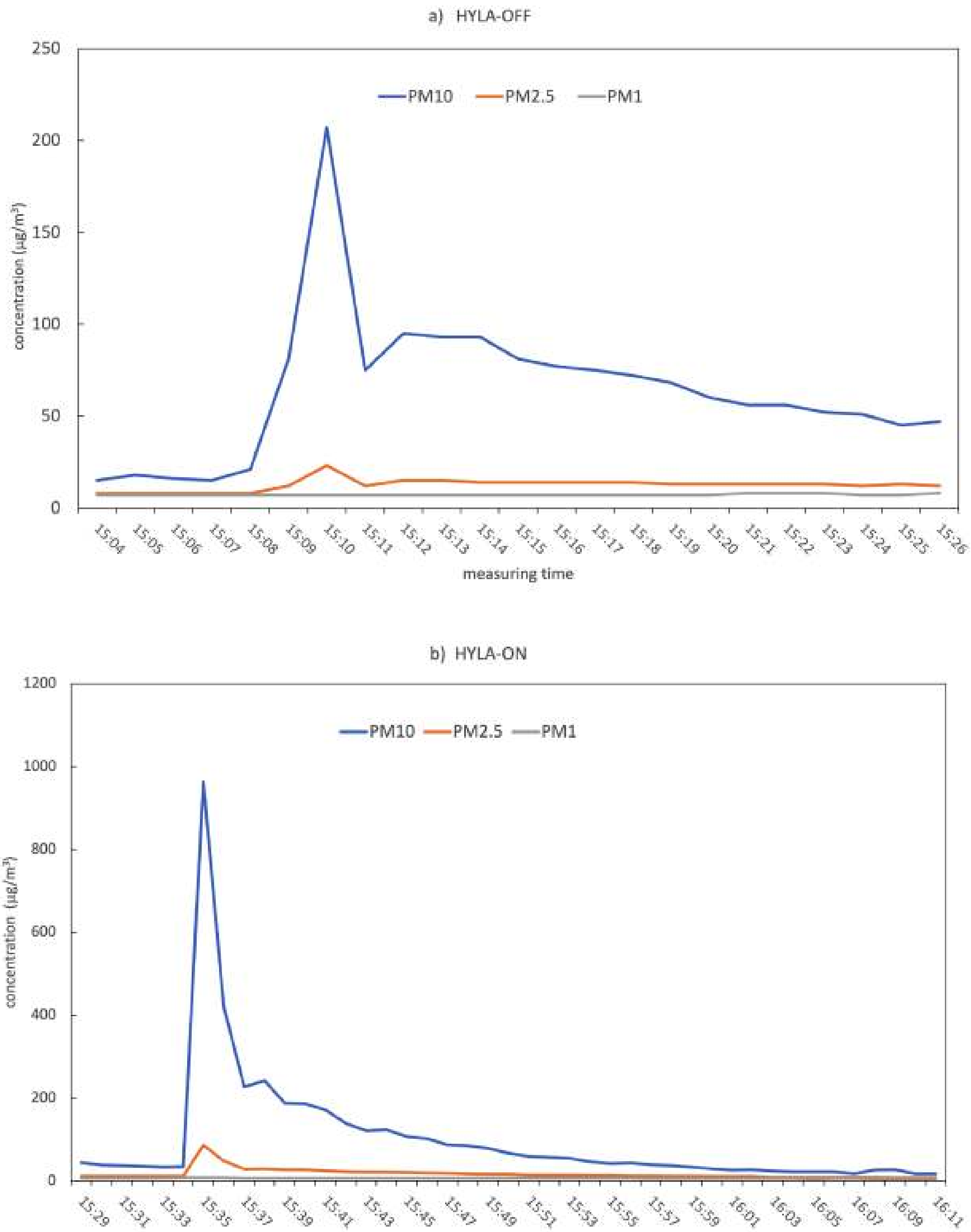

Figure 2. PM concentration with the HYLA device switched off (2a) and on (2b).

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 (Table 2) are concerned, the value of S parameter was also considerably higher with the HYLA 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 Figure 3, clearly highlighting high efficiency of the air purifier (the uncertainty was not calculated since the results shown are those obtained from the PM trends reported in Figure 1). This corresponds to a decrease of over 90% for PM10 and over 80% for PM 2.5. These values are in accordance with what reported by Zhan et al. [21] using air filtration devices.

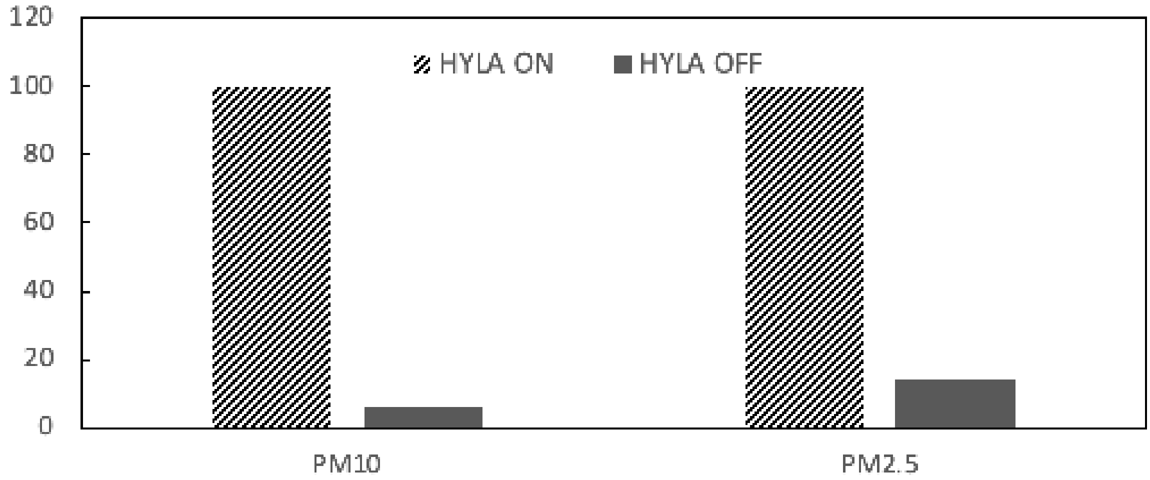

Figure 3. Relative efficiency of the HYLA air purifier in reducing PM10 and PM.2 with respect to natural particulate matter deposition.

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

Figure 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.

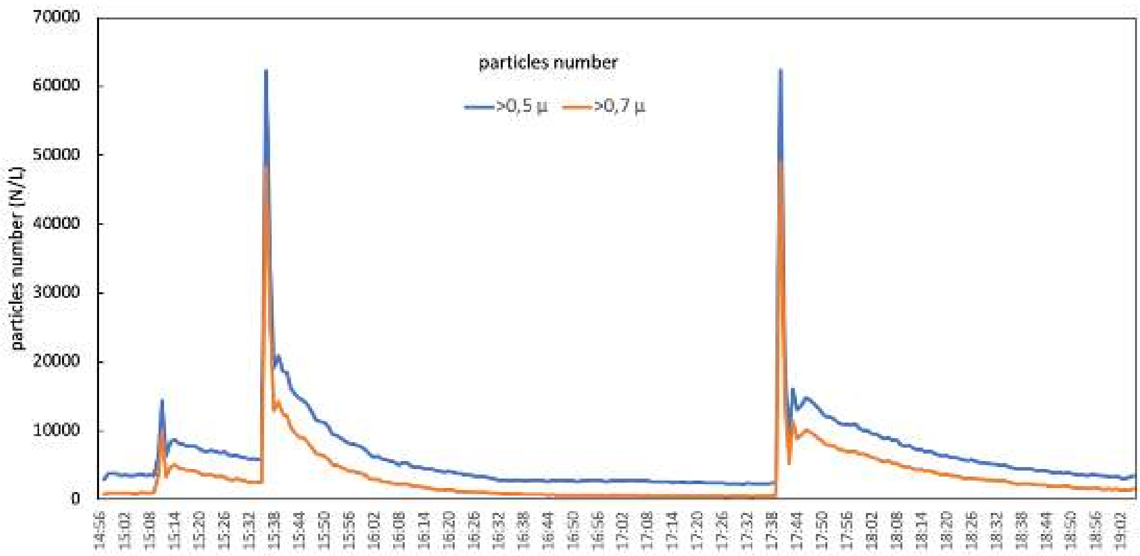

Figure 4. Particles number concentration during the measuring period (N/L= number of particles per liter).

In order to asses particles number during the two experiment with the instrument switched on or switched off (in this case peak 2 and 3 of figure 1 were considered), the curves dlogN/dlog(Dp) were obtained starting from the particles distribution over the 7 dimensional classes. 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.

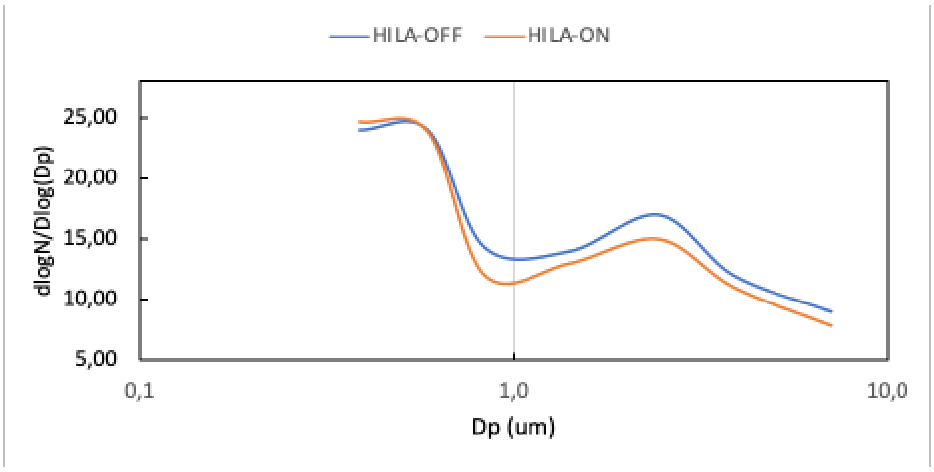

Figure 5. Particle number distribution calculated as dlogN/dlog(Dp).

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 [9].
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.
Figure 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 figure 6 and figure 7 and detected during the measurement (figure 7 represents an expanded zone of figure 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 of the peak, that is about a half of the previous concentration.
Subsequently, a prolonged exposure time of 30 min (peak 4) was chosen to obtain a very intense broad peak (out of scale). At 12:55 a.m., the HYLA system was turned on and a clear reduction of the peak was observed (first green arrow on the left fig. 7). At 1:25 p.m., after the signal stabilized and keeping the device on, a new exposure was made for a period of 30 min (peak 5).

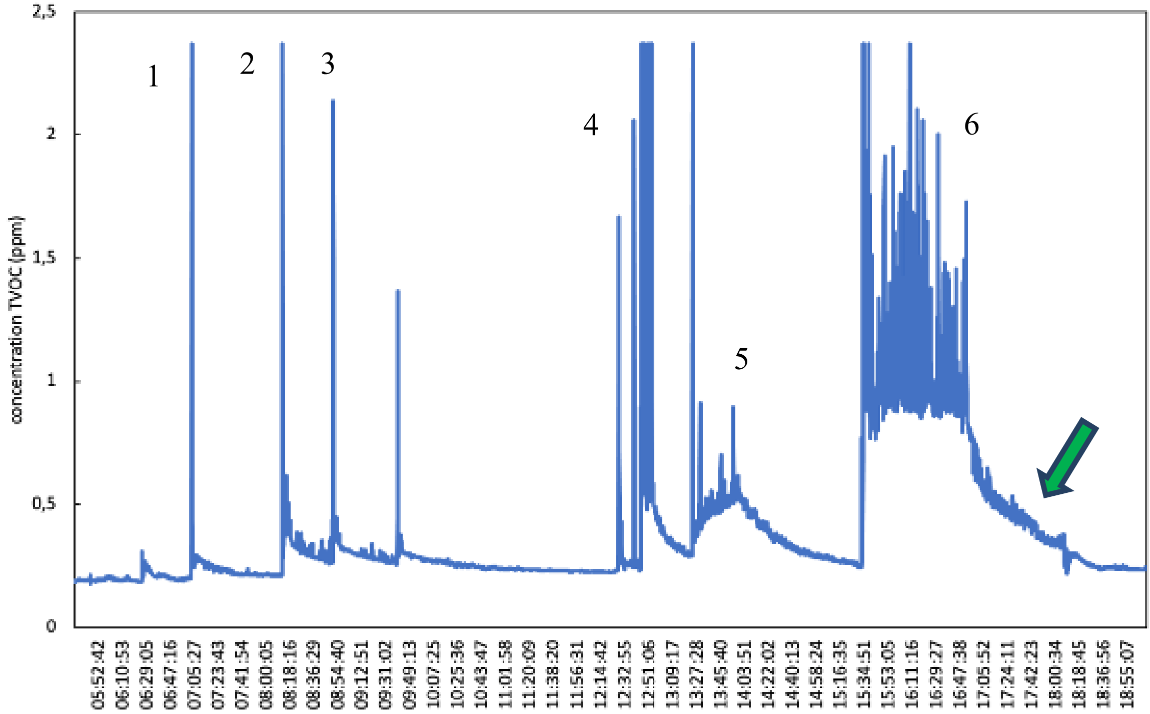

Figure 6. TVOC concentration during the experiment (ppm).

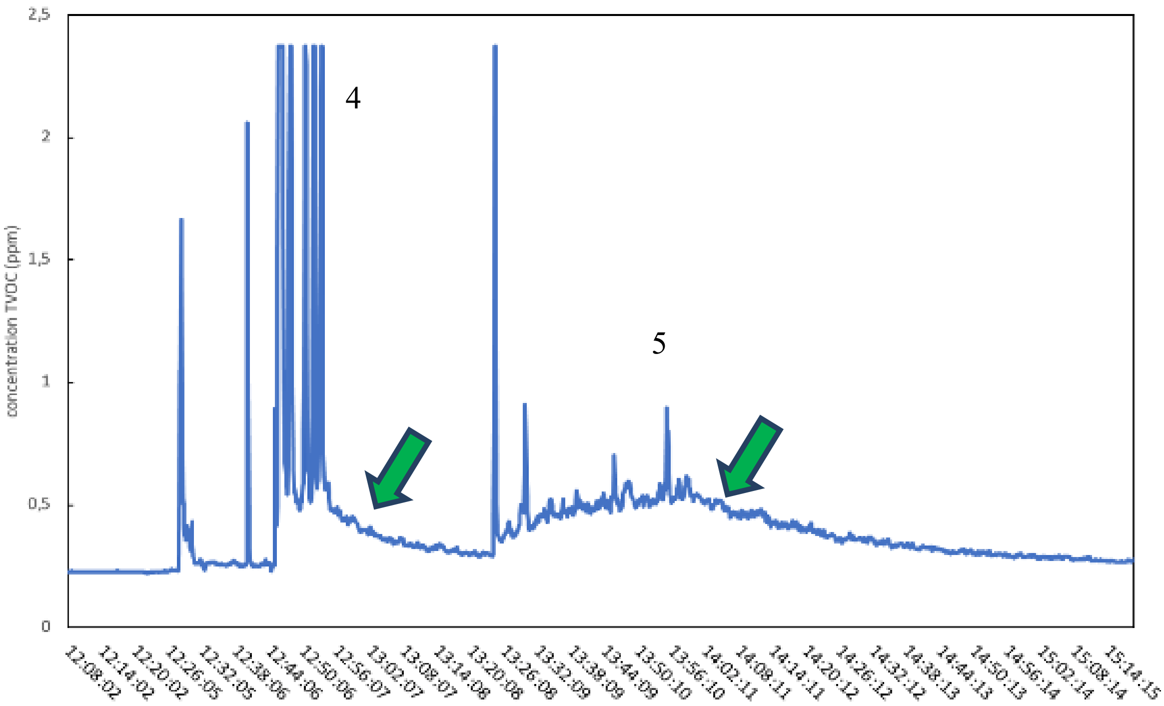

Figure 7. TVOC concentrations during the experiment (ppm): detail of fig. 6.

Contrary to peak 4, in this case we observe a significantly less intense signal with only one initial peak comparable to the signals observed with the device off, demonstrating that HYLA is very efficient in reducing TVOCs.
Finally, an exposure time of 1h was used to significantly increase the concentration of TVOCs in the room (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 hours, the signal reached the initial value (see the area indicated with the green arrow in Fig. 7). Considering peak 2 and peak 3 of table 3, it can be observed how a reduction of intensity over 40% is achieved.

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	1h (15.30 – 16.30)	broad peak	OFF

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 over 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 higher than 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 hours. 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, both with regard the reduction of 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.
When considering the need for improving indoor air quality in indoor environment as a measure of risk mitigation towards the diffusion of coronavirus SARS-COV2, air purifier systems could be successfully applied especially in crowded and critical environments (such as schools or waiting rooms of medical offices and emergency rooms, as well as offices, supermarkets, theatres, cinemas etc.). Moreover, a clear reduction in particles number, especially in the fine fraction, was observed during the device functioning, thus resulting in a positive impact on indoor air quality due to the ability to remove fine particles that can penetrate deeply into the lungs.

Author Contributions:
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[1], 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.

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). The costs of tests carried out during the assessment of the devices have been sustained by the manufacturer (Hyla Gmbh).

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